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REDUNDANT ACTUATOR
DEVELOPMENT STUDY

Final Report

By D. R. Ryder

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16. Abstract Current and past supersonic transport configurations have been reviewed to assess redundancy requirements for future airplane control systems. Secondary actuators used in stability augmentation systems will probably be the most critical actuator application and require the highest level of redundancy. Two methods of actuator redundancy mechanization have been recommended for further study. Math models of the recommended systems have been developed for use in future computer simulations. A long range plan has been formulated that will lead to actuator hardware development and testing in conjunction with the NASA Flight Simulator for Advanced Aircraft at Ames Research Center.					
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SYMBOLS AND ABBREVIATIONS

A	Piston area
B_1	Linkage freeplay
B_2	Hysteresis due to friction
C_p	Flow gain/pressure gain
D	Damping
D_{aero}	Aerodynamic damping
F_f	Coulomb friction
FSAA	Flight Simulator for Advanced Aircraft
F	Actuator force output
H	Feedback gain
K	Actuator dynamic spring
K_a	Servo amp gain
K_c	Centering spring rate
K_d	Failure detection gain
K_{dm}	Demodulator gain
K_E	Equalization gain
K_f	Feedback amplifier gain
K_i	Actuator input lever gear ratio
K_L	Open loop gain
K_p	Valve pressure gain
K_{S1}	Actuator structural spring
K_{S2}	Actuator rod spring

K_v	Valve flow gain
K_x	LVDT output
L	Actuator total stroke
LVDT	Linear Variable Differential Transformer
M_L	Load mass
P_L	Actuator load pressure
P_m	Maximum actuator ΔP
P_S	System supply pressure
P_T	Bypass pressure ΔP
S	Laplace operator
V	Input signal voltage
x	Output displacement
x_v	Valve displacement
β	Hydraulic fluid bulk modulus

REDUNDANT ACTUATOR DEVELOPMENT STUDY

By D. R. Ryder

1.0

SUMMARY

This report is submitted in compliance with contract NAS2-7653. Multiple redundant actuators applicable to advanced supersonic transport flight control systems have been studied. The study included the review of recent developments in redundant control systems and control requirements of supersonic transport configurations. Secondary actuators used in stability augmentation systems were found to require the highest level of redundancy. Two methods of actuator redundancy mechanization representative of those that will most likely be used in future airplanes have been recommended for further study. Actuator math models of the two methods of actuator redundancy have been developed that will allow investigation of wide range of actuator failures, mechanization of failure detection and channel equalization methods, and adjustment of actuator parameters to match the requirements of various advanced airplanes. A long range plan has been formulated that will lead to actuator hardware development and testing in conjunction with the NASA Ames Flight Simulator for Advanced Aircraft (FSAA) to allow investigation of pilot and control system interaction.

Any advanced supersonic transport airplane will have to be economically competitive with large subsonic airplanes. Economic supersonic flight will require taking advantage of all possible gains in aerodynamic efficiency and reductions in airplane weight. It will probably require using configurations that are unstable in the pitch axis. For these configurations to be safe and have acceptable handling qualities, the airplane stability must be augmented through the control system. Since the stability of the airplane then becomes flight critical, the control system reliability must approach that of the basic airframe.

Fault corrective capability that will meet the system reliability requirements and also satisfy the FAA regulations dictate flight control system configurations that can survive two failures and still remain operational. The performance level after failure may degrade to less than normal but must remain adequate to complete the mission. Safe operation after failure may require a restricted flight envelope.

Use of redundancy to achieve reliability has always been an accepted engineering design technique. However, the advantages of redundancy are not easily realized in control systems because of signal channel interaction, failure effects, performance degradation after failures, null shift with channel changes, and failure detection problems. If force summed multiple actuators are used to drive a single load, actuator load sharing becomes a concern. Methods of insuring proper load sharing can reduce load reaction stiffness, cause poor resolution, and may lead to dynamic instability if not properly designed and built. Monitoring used to effect the orderly shutdown of failure elements may cause inadvertent shutdown of good elements. All of these problem areas with respect to redundant actuators show a need for further study of actuator redundancy. The interaction of pilots and airplanes with redundant control system designs is important because of performance changes and control transients that occur with failure or actuator shutdown. The NASA Ames Flight Simulator for Advanced Aircraft (FSAA) is well suited to investigation of advanced control systems.

This report covers the initial portion of a study that will culminate in control system hardware (or mini-rig) connected to the FSAA. This initial portion of the study includes the selection of redundant actuator concepts that are representative of those that will most likely be used in advanced flight control systems, the development of math models of those systems, and formulation of a plan for the next phase of the study program.

3.0 STUDY TASKS

This study has been divided into four tasks. A report on the work performed in completion of the tasks is covered in this section.

3.1 TASK 1 - REVIEW OF REDUNDANT ACTUATION DEVELOPMENT FOR SST APPLICATION

3.1.1 Airplane Configuration and Control Redundancy Requirements

The starting point for this study was to review current and past supersonic transport configurations as well as non SST work to survey the various redundancy mechanization schemes used in both surface power actuators and secondary actuators. Secondary actuators are defined as small actuators used in a fly-by-wire, autopilot, or stability augmentation control systems as a stage of amplification and a method of converting an electrical signal into a mechanical displacement.

Examination of these configurations and their control requirements has led to two conclusions:

- o The minimum redundancy requirements for surface power actuators are basically the same for flight control surfaces on all advanced supersonic transport configurations.
- o The most stringent redundancy requirements will be set by stability augmentation systems used on unstable airplane configurations.

The discussion that follows develops the reasoning behind these conclusions.

Economic supersonic flight will require the lightest possible airplane. The need to minimize airplane weight reduces the permissible use of mass balance of control surfaces about the hinge line as a means of preventing control surface flutter. If mass balance is not used, the surface must be restrained by the surface power control actuators.

The Federal Aviation Regulations, Volume III, Part 25, paragraph 25.629, "Flutter, deformation, and fail-safe criteria," requires that an airplane be free from flutter after any single failure in the flight control system, plus any other "reasonably probable" single failure or malfunction affecting flutter. Hydraulic system failures are classified as "reasonably probable" by the FAA. Therefore,

when airplane design dictates that control surfaces be restrained by the flight control system to avoid the mass balance weight penalty, these requirements dictate a need for at least two surface power actuators and three hydraulic systems for each surface. As an example, the Concorde utilizes two surface power actuators per surface, each with a separate hydraulic supply, plus a third standby hydraulic system which can be switched to supply either actuator. This is an acceptable system only if a failure analysis shows that a single failure such as a leak in one actuator which could deplete a normal system and the standby system in combination with another hydraulic system failure is extremely remote.

Independent of considerations for suppression of surface flutter, surface power actuator redundancy is also influenced by the need to maintain control of the airplane flight path. The Federal Aviation Regulations, Volume III, Part 25, paragraph 25.671, requires, in part, that the airplane must be capable of safe flight and landing after any single failure, excluding jamming, in combination with any probable hydraulic system failure.

One form of redundancy to assure continuance of control function would be to use multiple aerodynamic surface segments, independently controlled, in each airplane axis. If actuator redundancy were not required for prevention of flutter, each surface could be controlled by a single actuator. Degraded, but safe, operation could be possible if one or more surface segments became inoperable.

There seems little doubt that the need for maximum aerodynamic efficiency and minimum weight in an advanced supersonic transport would prohibit consideration of either a multiplicity of aerodynamic control surfaces for control system redundancy or use of mass balance for flutter prevention. These two factors are sufficient to set the minimum redundancy level for surface power actuators. The most efficient and safe mechanization will be three surface power actuators per surface, each supplied by separate and independent hydraulic systems.

It has been shown in previous studies by Boeing and others that gains in aerodynamic efficiency and reduction in airplane weight can be achieved by placing the operating center of gravity aft of the longitudinal maneuver point. (References 2 and 3). The resulting unstable airplane must be augmented through the flight control system to provide acceptable handling qualities. If the stability of the airplane is critical such that loss of the augmentation means loss of the airplane, the control system reliability must approach that of the basic airplane. To achieve this level

of reliability, special considerations must go into the design. Such considerations include design simplification, derating of components, elimination of electrical connectors, and physical isolation of electrical wiring and hydraulic power. Even with these considerations redundancy is usually required to get satisfactory reliability from complex electronic control systems and actuators.

It is believed that for any future advanced supersonic transport, airplane requirements will dictate reliance on flight critical systems requiring a minimum of four augmentation channels or three channels appropriately monitored. This level of redundancy is the minimum required to insure continued safe control of the airplane after two failures.

3.1.2 Secondary Actuator Redundancy

The power levels associated with the electronic stability augmentation system must be kept at low levels as a matter of good design. These low level commands are required to command surface actuators that operate at high power levels. Converting the low level electrical commands to surface displacements controlled by hydraulic power requires several stages of amplification.

Review of current redundant actuation systems shows an almost universal use of secondary actuators as one of the stages of amplification. Using secondary actuators provides a convenient method of reducing four channels of augmentation signals to the command required for the two or three surface power actuators. Secondary actuators provide a single valued mechanical input which allows utilization of simple reliable mechanical surface actuators.

The most prevalent methods of forming a single valued mechanical signal at the secondary actuator output are force summation, displacement summation, and active/standby operation. These mechanization methods are illustrated in figure 1. Rate summing of signals is another method of secondary actuator mechanization being used.

3.1.3 Survey of Current Actuator Redundancy Mechanization

The survey of current redundant actuation systems resulted in examination of ten flight control systems listed below. With the exception of the commercial airplane systems (747, L-1011 and Concorde), all meet the operation capability required for an advanced supersonic transport.

Control Systems Examined

1. Boeing SST Horizontal Stabilizer Actuation System
2. Space Shuttle HRM-A Secondary Actuator
3. Space Shuttle HRM-C Secondary Actuator
4. NASA F8-C Fly-by-Wire Secondary Actuator
5. General Electric 680J Secondary Actuator
6. MRCA Secondary Actuator
7. Boeing 747 Elevator Control System
8. Lockheed L-1011 Longitudinal Control
9. Concorde Elevon Control
10. LTV 680J Electromechanical Secondary Actuator

Comparison Factors

This section contains a discussion of the important factors used by the investigator to evaluate the systems. This discussion is placed before the description of each system to aid the reader in identifying system differences. Description of the LTV electromechanical secondary actuator is not included. Boeing SST studies indicated that this type of system would have difficulty meeting FAA requirements for flight critical systems.

1. Load Sharing

Load sharing is a measure of the ability of multiple actuators to work together in positioning a common output. Load sharing is a problem peculiar to force summed actuators since, obviously, there is no force fighting in an active/standby system when only one system controls at a time or in a position summed system where forces of individual actuators are additive.

There are several methods used in achieving load sharing. Ideally, it is desirable that the load be divided equally among redundant actuators to eliminate any force fighting. However, since each actuator tries to position the load according to the net command it senses, any differences in the effective commands cause force fighting to occur between the actuators. By net command differences are meant the tracking errors that arise due to tolerance buildup in each actuator servo loop and actuator installation. To minimize force fighting in multiple actuators and assure acceptable sharing of the load, four methods are commonly used:

- a. Provide accurate tolerance control of the feedback loop of the actuator.

A mechanical actuator is fairly easy to mechanize with good tolerance control because of the manufacturing accuracies that can be obtained and the unchanging nature of the mechanical linkages.

As an example, if a single mechanical servo valve with multiple control sections is used to control multiple actuators, the valve can be machined to tolerances which assure reasonable load sharing usually within 10 percent of system force capability.

An electrically controlled actuator has elements such as summing amplifiers, demodulators, and feedback transducers which can change characteristics with time, temperature and power. It is generally accepted that the tolerances associated with an electronically controlled actuator are significantly greater than for a mechanically controlled actuator.

- b. Provide sufficient compliance to reduce force fighting.

In some applications the structural compliance between actuators can be designed to reduce force fighting. In other applications feeding back deflections of the actuators reaction structure has been sufficient to provide the desired load sharing. When structural feedback or compliance between actuators is insufficient or undesirable from other aspects, static pressure feedback has been used to provide the required compliance. Feeding back a signal proportional to differential pressure has the effect of increasing the actuator compliance, thereby reducing the force differences. This signal can be an all mechanical feedback to a mechanically controlled actuator or can be electrical to an electronically controlled actuator. However, there is a limit to the amount of compliance that can be achieved without reducing the overall stiffness below a minimum allowable level. This method has been used successfully where the inputs are reasonably matched, such as a set of surface power actuators signalled by a common mechanical command or in secondary actuators where the output load is small.

c. Equalization to average load.

For cases where the actuators are required to operate into large aerodynamic loads and have uncontrolled input mismatch the pressure feedback system requires modification to be useful. The individual actuator feedback must be compared to the average load. Computation of the average load and the individual difference from averaging require cross channel comparison. This method does not degrade actuator stiffness.

2. Input Mismatch

Although mismatched inputs to a multiple actuator system create a load sharing problem, methods of eliminating or minimizing mismatch require separate discussion. Differences in commands (input mismatch) that can build up due to tolerances in an electrical control system from sensor to actuator can be quite high, as much as a quarter of full scale command, unless some design action is taken to prevent such buildup. It should be noted that difference in commands generated by actuator loop tolerances are an order of magnitude less than those generated by computational elements in the upstream portions of the system.

It is advantageous to treat the computation errors and actuation errors independently by inserting a synchronizing stage between the two functions. The synchronizing stage provides a single valued command and may be an electronic voter or a mechanical output of a secondary actuator arrangement. Some of the advantages of synchronizing are:

- o If the surface power actuators can be isolated from the upstream command differences, the task of providing adequate load becomes easier, permitting a simpler and more reliable mechanization of the power stage.
- o A secondary actuator that provides a synchronizing stage can operate at relatively low force levels. If properly designed, it can provide the high levels of confidence, freedom from catastrophic failures, and immunity from outside interference.

Although a secondary actuator arrangement can provide a single valued command to a set of surface power actuators, the problem of input mismatch is not eliminated but transferred to the secondary actuator. However, the magnitude of the problem is less severe because the secondary actuators operate at significantly lower force levels. The methods of secondary actuator mechanization to deal with the mismatch problem are itemized below.

o Force Voting

By force voting several actuators on a common output an output representing the mid value of all commands can be achieved. Feedback can be used to increase input mismatch allowables. In some applications the only possible way of controlling command differences may be the use of electronic signal conditioning to provide less of an input mismatch.

o Active/Standby

Usually the active actuator is commanded by a single electronic channel and mismatch is of no concern during operation. Mismatches between the commands of the active and the standby channel are of concern, however, and must be minimized to avoid large surface transients upon switching from active to standby actuators.

o Position Summing

Position summing secondary actuators differently results in a single output which is the average of the input commands.

o Rate Summing

Rate summing secondary actuators allow the individual channels to cancel command differences by differentially summing rates.

3. Failure Insensitivity

Failure insensitivity is the ability of the redundant system to accept a failure and automatically continue operation with a minimum surface transient. If the system performs a critical function, operation must be maintained in the presence of a failure; i.e., be fail operational. However, a fail-operational system does not insure minimum surface transients. The

criticality of transients has an impact on the detail design of the system. Several means of providing fail operational capability are discussed below.

- a. Fail-operational capability can be achieved by majority voting three or more active actuators. With three active channels, operation continues after the first failure. With four channels, operation continues after two failures, if the first failed channel is disconnected before the second channel fails.

Majority voting can be mechanized either by force voting or by displacement summing. In the force voted system the failed channel is automatically overpowered by the remaining channels and the magnitude of the surface transient can be insignificant. Displacement summing provides an average output but has an inherent surface transient and a steady state null offset. The magnitude transient is dependent upon the closed loop system response.

- b. Another approach is to use a monitor and comparator or failure detection device to assess which channel of the system has failed and automatically disconnect it. This approach may be used to maintain fail-operational capability with fewer channels if each channel is monitored for failures independently. Another method of reducing the number of working channels is to add a model of a working channel and use cross channel monitoring for failure detection. While this extends operational capability with one less active channel its effectiveness depends on how well the model matches the actual hardware. In certain applications, where actuators are large and where weight is critical, the model approach may provide a way to minimize the overall weight.
- c. When it is possible to use multiple aerodynamic segments, independently controlled, degraded but safe operation may be possible with one or more segment failed. This feature is used in current airplanes. However, as explained previously, advanced supersonic airplanes will probably be limited in use of control surface redundancy particularly in the longitudinal axis because of the need to attain maximum aerodynamic efficiency.

4. Failure Detection Capability

Failure detection and indication of failures during operation must be provided so that the failed channel can be turned off to preserve the integrity of the system. The failure detection system must be designed to detect all types of failures; active, passive, oscillatory, slow overs or ramps which could themselves or in combination with another failure produce an unsafe situation.

In some mechanizations, immediate failure detection is required to keep the airplane safe. For instance in an active/standby system rapid detection of the first failure and automatic switching to the standby is mandatory to avoid large surface transients which could overstress the airplane.

The ability of the failure detection system to sort out legitimate failures from apparent failures such as might occur due to adverse tolerances has an equivalence in reliability. If the failure detection system trips a channel off inadvertently due to an apparent failure, the equivalent mean-time-between-failure (MTBF) for the system may be significantly affected.

5. Self Testing Capability

Preflight self testing will be required to detect those failures that may not normally be detected by the in-flight failure detector. The test should be simple but yet complete enough to assure with confidence that the redundant system is in satisfactory condition. It is desirable that the self test be of the push-to-test for a "Go," "No-Go" indication. Quantitative measurements should be avoided, in favor of more simple continuity testing. Systems should be able to be tested by using the normal failure monitors to sense the presence of an inserted test signal.

The quality of self test features also has an equivalence in reliability since testing reduces the exposure time to an undetected failure.

6. Reliability

The reliability requirement for a particular system is based on the function it performs, the consequences of failure, and the duration of each mission. Primary assessment will assume the requirement for a system to remain operational after two failures. However, as a system becomes more complex, more failures will occur and reduce overall reliability even though the requirement to remain operational after two failures has been met.

7. Simplicity

While redundancy increases in-flight reliability and provides various degrees of flight control operation dependent upon requirements, redundancy does increase the initial procurement cost as well as maintenance cost and is reflected in increased maintenance work load.

If the function can be done with a less complex mechanism, usually it can be done more reliably, as there are fewer things to go wrong. Also, the cost will be less. As noted above, failure detection and checkout capability must be included in the system definition, and this can grow to be a very significant part of the total system complexity.

3.1.3.1 Boeing SST Horizontal Stabilizer Actuation System

The all-moving horizontal stabilizer of the Boeing SST was powered by four surface power actuators arranged side by side, each supplied by a separate and independent hydraulic system. The actuator size was chosen to provide hinge moment capability for safe control and to meet flutter requirements with any two hydraulic systems failed. Though three surface actuators would have met redundancy requirements, four actuators were used in order to reduce the amount of installed hinge moment capacity. If three actuators had been used, each would have been required to meet the minimum hinge moment requirement and the total capacity would have been three times the minimum. When four actuators are used each can satisfy one half the minimum requirements. The total installation has only two times the minimum requirement. The stability augmentation system and secondary actuators were also four channel to provide operational capability after two failures.

The overall SST pitch control system is shown in figure 2. The secondary actuators used for stability augmentation were termed EC servos on the SST because they also received "electrical command" (EC) signals from the pilot controls. The output of the secondary actuator was summed with the pilot's mechanical input system on a differential link. The secondary actuators were integrated with (built as a part of) the surface power actuators as shown in figure 3. This mechanization has the advantage of having the summing linkage that receives the secondary actuator output protected inside an oil filled cavity. The outputs of the four secondary actuators were force voted on a torque tube (identified as the EC sync shaft and detent in figure 3). Each actuator connection to the torque tube was through a detent mechanism that allowed motion of the torque tube with any secondary actuator jammed. If a secondary actuator was shut off or received an erroneous signal, those remaining could provide inputs to all four surface power actuators. If a secondary actuator jammed, the surface power actuator that it was a part of could not receive proper signals and had to be shut off.

The secondary actuator piston was controlled by an electrohydraulic servovalve with the position loop closed electronically in a servo amplifier. Across each piston was connected a spring detented bypass valve set to open when

the differential pressure reached 292 psi which equaled a reflected load on the piston of 150 pounds. The bypass valve motion versus differential pressure is shown in figure 4. The valve motion was converted to an electrical signal by a linear differential transformer (LVDT). Pressure unbalances of either a steady state or dynamic nature that occurred between channels were corrected by feeding back to the servo amplifier two voltages; one proportional to the displacement of the bypass valve to equalize dynamic differences in commands, and one proportional to the integral of the bypass valve displacement to equalize any steady state differences in commands whenever the proportional equalization signal exceeded a chosen threshold for a set interval of time, the channel annunciated to the flight crew. The flight crew then manually shut down the secondary actuator portion of the failed control channel.

If two channels had failed and had been shut off, the remaining two secondary actuators remained operational. Upon a third failure, the system force voted to null by the centering springs of the shutoff channels, rendering the system passive. This mechanization method minimized surface transients for any single failure and did not rely on failure detection for safety.

3.1.3.2 Space Shuttle HRM-A Secondary Actuator

The servo actuator is an electrohydraulic, three-channel, active/standby configuration developed by Hydraulic Research and Manufacturing Company (HRM). The actuator description was obtained from reference 6. This actuator is an implementation of redundant hydraulic control employing monitoring to attain the capability to sustain two failures and continue to operate.

A modular design approach was used. The actuator (figure 5) consists of three independent systems or modules with complete hydraulic isolation that control a triple tandem piston. Only one system controls the actuator at any one time. If a malfunction occurs in the controlling system, a switch is made to a standby system, thus, there is neither a loss in output force nor a performance degradation after the failure. Each system has two electrohydraulic servovalves, one which controls flow to its piston and one monitor servovalve which monitors the second stage spool position of the active servovalve.

These six servovalves are modified HRM model 25 two-stage nozzle flapper valves. The servovalve consists of an

electrical torque motor and hydraulic output stage. The output stage of the active valve is a closed center slide valve which means that the spool is designed to block fluid flow when at the null position. Current flowing in the torque motor coils induces a torque in the armature, which pivots the flapper slightly toward a nozzle. This motion unbalances the hydraulic amplifier circuit, causing a pressure difference to be generated between the two end chambers of the second stage spool. This pressure difference creates motion in the second stage spool. Spool position is reflected as feedback torque on the torque motor armature by means of the mechanical feedback spring. Thus by closing the servo mechanism loop, spool position is proportional to input current. Rectangular metering slots in the second stage spool cause flow proportional to input current.

The HRM model 25 valve has been modified by adding a second monitor flapper and nozzle (figure 6). The only difference between the active servovalves and the monitor valves is that the monitor valves have a blank spool in place of the second stage spool and sleeve. Both of them have a monitor flapper and nozzle. The function of the monitor flapper and nozzle is to develop pressures proportional to the position of the second stage elements of the active and monitor valves. These two pressures are fed to opposite ends of a comparator spool. If no malfunction occurs these two pressures will vary but will remain equal in magnitude and the comparator spool will remain centered.

The system operates in the following manner. Referring to figure 5, after hydraulic pressure is available, all three "on" solenoid valves are pulsed to engage the system. Once pulsed, each solenoid valve is held on its seat by its system hydraulic pressure. This pressure drives the three engage valves against the engage valve spring located at the left end of the system 3 engage valves. This activates system 1. The active servovalve in system 1 controls the actuator. The pistons of systems 2 and 3 are bypassed and the output ports of "active" valves 2 and 3 are blocked by their engage valves.

If a malfunction occurs, the second stage positions of the active and monitor valves will differ. This will cause a pressure difference on the comparator spool creating motion of the spool. When the pressure difference exceeds a pre-determined threshold, motion of the comparator spool will dump the system 1 pressure that has been holding the engage valve against the spring to return. The engage valve moves

to the right until it is stopped by the system 2 position piston. System 1 engage valve is then in the bypass position. The bypass position connects the cylinder ends of system 1 piston and blocks the output of the active servovalve of system 1. System 2 will then become the active channel and will operate in exactly the same way as system 1. The failure threshold of the comparator can be easily varied. After the optimum threshold is determined by test, it will remain fixed in the design.

If a malfunction occurs in system 2, a switchover to system 3 will be accomplished in the same manner. If system 2 has previously failed, the switch will be from system 1 to system 3. In this design, only a channel that is operational is capable of gaining control of the actuator.

A third failure will cause the actuator to fail in a bypass mode on all three systems. System failure is detected by a pressure switch on each comparator valve.

Pressure loss in any system that exceeds a predetermined threshold will cause the ball in the solenoid valve to unseat, thus, switching to the next channel.

After malfunction, any one system will not come back on line until the "on" solenoid valve is pulsed. If the malfunction has been corrected, input to the comparator from the active and monitor channels will be identical, indicating the system is capable of normal operation. If the malfunction is still present, the system will immediately switch off line as before.

Attached to the actuator output are four position feedback linear variable differential transducers (LVDTs). One LVDT is dedicated to each of the three channels for servo position feedback and all LVDT signals are used for LVDT failure detection logic. This logic uses a cross channel failure detection method. Each LVDT signal is compared with the signals from all other working LVDTs. A fail decision is made if the signal of that LVDT differs appreciably from that of the other LVDTs. The failure threshold is an error voltage equal to that generated by displacing the actuator five percent of full travel. The detection of a failure energizes a latching relay which provides a positive d.c. bias voltage to the monitor servo amplifier. This causes the hydraulic logic to disengage the channel with the failed LVDT.

3.1.3.3 Space Shuttle HRM-C Secondary Actuator

This servoactuator is an electrohydraulic, three-channel, force-summing configuration developed by Hydraulic Research and Manufacturing Company (HRM). The actuator description is based on information given in reference 7. This actuator is an implementation of redundant control employing individual channel monitoring using duplicated signal paths to provide failure monitoring for channel shutdown.

A modular design approach is used to provide the required redundancy. This actuator (figure 7) consists of three independent systems or modules with complete hydraulic isolation controlling triple tandem pistons. All systems that are operating control the actuator. When a malfunction occurs in any system, that system is blocked by a shutoff/bypass valve, and the force output capability of the actuator is decreased proportionally. The actuator piston for that system goes into a bypass mode. Each system has an active two stage electrohydraulic servovalve which controls flow to its piston and a second electrohydraulic servovalve which is used to monitor the second stage spool position of the active servovalve. The active and monitor valves are identical to those described in section 3.1.3.2. The pressures induced by the monitor flapper and nozzle portions of the active and monitor valves are fed to opposite ends of a comparator spool. With normal operation, the pressures will vary but will remain equal. Motion of the comparator spool beyond a predetermined threshold due to unequal pressures is an indication of failure.

The actuator operates in the following manner. Referring to figure 7, after hydraulic pressure is available, the three "on" solenoid valves are pulsed to engage the actuator. Once pulsed, the solenoid valves are held on their seats by system hydraulic pressure. This pressure drives the three shutoff valves against their springs and activates the three systems. The active servovalve in each system controls each section of the actuator.

If a malfunction occurs the outputs of an active and monitor valve will differ. This will cause a pressure difference on a comparator spool causing motion of the spool. When the pressure difference exceeds a predetermined threshold, motion of the comparator spool will dump the supply pressure that had been holding the shutoff valve of that system to return. The shutoff valve of the failed system will be forced by the spring pressure into a bypass position. The bypass position blocks the output of the active servovalve of the failed

system and connects the cylinder ports to permit the actuator to operate with the remaining controlling systems. System failure is detected by a pressure switch on the comparator valve.

The failure threshold of the comparator can be easily varied by either changing the spring rate or overlap of the comparator spool. Once the optimum threshold is determined by test on a particular system it will remain fixed.

If a malfunction occurs in a second system it will be also placed into a bypass mode. The remaining system will continue to control the actuator. The sequence of system failure is no problem. All systems are operational and only a failed system is switched out. A third failure will cause the actuator to go to a bypass mode on all three systems.

After a malfunction a failed system will not come back on line until the "on" solenoid valve for that system is pulsed. If the malfunction has been corrected, pressure will hold the solenoid valve ball on its seat, the input to the comparator spool from the active and monitor valves will be identical, the shutoff valve will be pressurized, and the pressure switch will cycle, thus returning the system to normal operation. If the malfunction is still present, the system will immediately switch out as before.

Differential pressure transducers are used to provide pressure feedback information for an electrical pressure gain reduction circuit. A pressure transducer sensing pressure across each piston generates zero voltage at zero differential pressure and 20 millivolts at 3000 psi differential pressure. The differential pressure feedback reduces the pressure gain (per system) from 6000 to 9000 psi per milliampere to approximately 750 psi per milliampere. This gain reduction reduces the possibility of deadband resulting from actuator force fighting.

Attached to the actuator output are four position feedback linear variable differential transducers (LVDTs). One LVDT is dedicated to each of the three systems for servo position feedback and all four LVDT signals are used for LVDT failure detection. A cross-channel failure detection method is used. Each LVDT signal is compared with the signals from all other working LVDTs. A fail decision is made if the signal of the LVDT differs appreciably from that of the other LVDTs. The failure threshold is an error voltage equal to that generated

by displacing the actuator five percent of full travel. The detection of an LVDT failure energizes a latching relay which provides a positive d.c. bias voltage to the monitor servo-amplifier. This causes the hydraulic logic to disengage the channel with the failed LVDT. By using this LVDT failure detection method the number of LVDTs required to make the actuation mechanization work is reduced from 6 to 4.

3.1.3.4 NASA F8-C Fly-By-Wire Secondary Actuator

The system consists of four electrohydraulic control channels and triple tandem pistons. One of the control channels has an active electrohydraulic servovalve plus a monitor servovalve. Referring to figure 8, this is identified as servo system 1. The system is an active/standby configuration which consists of the monitored primary channel (servo system 1) with hydraulic logic failure detection and three force summed standby channels with electronic failure detection. The total package is supplied by two separate hydraulic supplies. The design provides complete hydraulic system isolation.

Servo system 1 consists of two two-stage, flapper nozzle servovalves, one active and one a monitor. These valves are the same as those described in paragraph 3.1.3.2. The active valve controls the actuator output and is monitored hydraulically by the monitor servovalve and hydraulic comparator.

If a failure occurs, the outputs of the active and monitor valves will differ. This will cause a pressure difference on the comparator spool, causing spool displacement. When the pressure difference exceeds a predetermined threshold, displacement of the comparator spool will dump to return the supply pressure holding the engage valve. The engage valve of servo system 1 will be forced by spring force into a blocked position. The blocked position blocks the output of the active servovalve of system 1. The failure threshold of the comparator can be easily varied by spring rate adjustment or overlap of the comparator spool.

After hydraulic pressure is applied and the No. 1 solenoid valve is energized to engage the system, the solenoid valve is held on the seat as long as electrical power is supplied. System 1 can be manually disengaged by de-energizing the solenoid.

Upon a failure of the primary channel, the system 1 failure indicator will provide an electrical signal to automatically

energize the standby channel solenoid valves (servo systems 2, 3 and 4) and thereby transfer control to the three channel, force-summed standby mode of operation. Differential pressure transducers are provided across each of the cylinder ports in order to provide signals which can be used to determine failure status. Provisions are made for manual on-off control of each of the four (4) channels.

Second failures occurring in the standby system will result in control with some degree of degradation. When one of the three channels is deactivated, the total servoactuator force output is degraded by one third ($1/3$) while the system response remains unchanged. When a second channel is deactivated, the system response is unchanged while the force output is reduced by an additional third. Upon complete de-energization of all solenoid valves, the triplex actuator is bypassed. Piston and seal friction are the only constraints on the piston when totally de-energized. The standby system force-shares three three servovalves with no deadband in the position control loop and uses no force equalization network. Avoiding equalization is primarily a result of using single-stage jet pipe servovalves which have a considerably lower pressure gain than two-stage valves.

3.1.3.5 General Electric 680J Secondary Actuator

The General Electric 680J Secondary Actuator system is an electrohydraulic four channel, force voting configuration. The secondary actuator is comprised of four individual modular elements, each of which is a small actuator, whose force outputs are summed on a rotary summing shaft as shown in figure 9. The small actuators are connected to the summing shaft by rocker arms.

One version of the actuator assembly has a centering mechanism that returns the entire system to center if all channels are shut off or if all hydraulic pressure is lost. The centering mechanism is held disengaged by pistons in each actuator element. Any one piston is sufficient to keep the centering disengaged. Another version is identical except that in place of the centering mechanism, a braking mechanism is provided. In case of shutdown the summing shaft is held in its last position by the brake. The braking version was developed for longitudinal control systems where maintaining the pitch control surface in the last position held before failure was a requirement.

Each individual small actuator element is dedicated to one control signal channel. Figure 10 shows a cross section of a typical single actuator element. Each element is driven by a single-stage jet pipe electrohydraulic servovalve. Each element has a separate LVDT to provide position feedback. The normal mode of operation is for all four elements to operate at the same time. The single-stage jet pipe valves have low enough pressure gains that interchannel input command differences can be held small enough to eliminate deadband in the output. The differential pressure across each channel's piston head is monitored by a differential pressure sensor which provides electrical information which can be used for cross channel monitoring and/or comparison. When the command to one channel differs from the other it will force fight the other channel and develop a differential pressure relative to the others. When the differential pressure exceeds a predetermined level, electronic logic will indicate that the element has failed and initiate a shutdown by de-energizing the element's solenoid-operated shutoff valve.

The same shutdown sequence is repeated when the second channel fails. However, upon third channel failure the electronic logic will shut down both remaining elements since it is not possible to determine which of the remaining two elements is good.

3.1.3.6 MRCA Secondary Actuator

The four channel, force-voted, rotary output actuator, shown in figure 11, was developed by Elliott Flight Automation, Ltd of England, under a Ministry of Technology contract to develop a fail-operational stability augmentation system. It is presently in production by Fairy Hydraulic, Ltd for the NATO Multi-Role Combat Aircraft (MRCA).

The actuator is normally utilized as a force summed position servo. Separate and isolated servoamplifiers are used for each of the four channels to sum the position command input and the position feedback and provide a drive for the electrohydraulic servovalve of each channel.

The system is comprised of four separately controlled small electrohydraulic actuators which are individually coupled to a common output member by clutch plates rotating around the common output shaft. Each plate has six tapered lugs which engage in six tapered holes in the plate fixed to the common output shaft. The plates are held in engagement by applying hydraulic pressure to the outside of the clutch plates driven

by the actuators. Any difference in position between an individual actuator and the common output causes the tapered lugs to ride out along the leading edge of the tapered hole so that the clutch plate is at a larger distance from the driven common output plate. For differences less than $\pm 10\%$ of the total stroke the actuator force is still transmitted, but for larger differences the clutch plate becomes disengaged. Positive disengagement is then assured by the action of the spring loaded member which automatically inserts itself between the plate driven by the disengaged actuator and the common output member. Sideways movement of the clutch plate end of the individual actuator output shafts is allowed by the knuckle joints at each end of the actuator connecting shaft. The sideways motion of the clutch plate is sensed by a switch which transmits a failure indication to the pilot.

The ± 0.5 inch (12.7 mm) travel of the individual actuators is converted to ± 20 degrees of output lever rotation so that the output stroke can be selected by the length of the output lever.

To avoid disengagement of all four actuator channels due to an excessive transient load on the output or to a temporary loss of electrical supplies, a gate mechanism operates on the actuator output plates such that if any two actuators become disengaged, all the available travel in the mechanism is taken up and no further disengagement can take place.

In addition to the electrical position feedback there is a low-gain mechanical feedback to center the actuator in the event of the loss of electrical power. In other words, the actuator will center automatically independent of electrical power when either hydraulic supply is on. This action is equivalent to mechanical spring centering which is the conventional but heavier method. The mechanical feedback applies a force of sufficient magnitude to the armature of the two-stage servovalve to cause the actuator to return to the mid-position. The gain of the mechanical feedback is so low that it does not affect the performance of the actuator which is dominated by the electrical feedback gain.

3.1.3.7 Boeing 747 Elevator Control (Autoland Option)

This system uses two dual primary surface actuators that are signalled by the force voted output of three secondary actuators. Two other surface power actuators are signalled by the outputs of the dual actuators. A simplified schematic of the basic system is shown in figure 12, and a basic system block diagram is shown in figure 13. The system consists of three

Breakout of one or two detents will be caused by large differences between the secondary actuator control piston positions. This can either be caused by a failure in the autopilot, servo amplifier, electrohydraulic valve, or can be caused by inherent manufacturing tolerances between channels. The simplest method to accomplish failure detection was found to be a comparison of each secondary actuator position to the summed output position. These same signals are used for equalization.

When the difference between the control piston and the summed output position exceeds a limit greater than what can be expected due to maximum manufacturing tolerances for a certain time, the system is considered to have a failure. (Presently this limit is set for 7.5 degrees and 1 second for the 747).

In order to avoid nuisance warnings and/or disengagements, this detection level must be higher than differences generated between channels when maneuvering.

3.1.3.8 Lockheed L-1011 Longitudinal Control

The L-1011 pitch control is provided by a hydraulically powered horizontal stabilizer with mechanically geared elevators. Four independent hydraulic systems provide power to four surface power actuators, any one of which is capable of control of the airplane.

Four autopilot channels are used to control the airplane in the fail operational autoland mode. The four autopilot channels provide signals to two autopilot actuators (secondary actuators) which command the four surface power actuators through the mechanical control system. The method of summing the two actuators is shown in figure 14. The two autopilot actuators work in a master-slave arrangement where the master actuator has a force advantage and overpowers the slave actuator in order to eliminate the deadband that would result from differences in output between the two channels. Each secondary actuator output is measured by dual LVDTs to provide a separate feedback signal to the two autopilot channels that control each actuator.

The four autopilot channels are in a dual-dual arrangement as shown in figure 15 where a fault in one dual channel shuts down that channel and not the other. All four signals are voted just ahead of the servoamplifiers and all servoamplifiers receive identical input commands. The outputs of each pair of servoamplifiers are compared to detect amplifier failures.

separate autopilots, each driving a separate closed loop position servo (secondary actuator). Each secondary actuator displacement is proportional to its respective electrical command signal. In the schematic, the three actuator control pistons operate into a common output through preloaded detents. A pilot feel system that provides centering is also connected to the output. This common output could be any type of linkage connecting the three pistons and the centering mechanism. To provide for triple channel, dual channel, or single channel operation, each detent can be disengaged such that no force is transmitted from the disengaged channel to the common output. The characteristic of the detents when engaged are such that only a small incremental force is transmitted to the common shaft after the preload is exceeded (i.e., there is a low spring gradient after detent breakout).

With all three detents engaged (triple channel configuration), the spring force and any friction and power actuator valve loads are reacted by three detent forces with the maximum force output triple that of a single channel. With no failures, all three control pistons move in a synchronized fashion. With a single failure, the system continues to operate even if the failed channel is not disconnected.

When the three autopilot commands are of different magnitude, due to tolerances, a disagreement will exist between the three actuator pistons. This disagreement must be taken up by the detents, forcing two of them to yield. If the centering spring is disregarded, the detents in the high and low channels will be out-of-detent in opposite directions. If the forces from these two detents balance each other, no force will be required from the detent with the midvalue position and the output will be that of the control piston with the midvalue. When the centering spring is considered, the force required to drive the centering spring must be obtained from the midvalue channel's detent. The system will select the midvalue of the three control piston positions as its output.

In dual and triple channel operation, manufacturing tolerances between the pitch integrators and null offsets in the glide slope beam receivers can cause a steady integration which would result in a hardover elevator command in the non midvalue autopilot channel(s). To avoid this, an equalizing signal must be fed to the pitch integrator. The difference between each secondary actuator control piston position and the summed output position is used for the equalization signal. This signal is a measure of each actuator's position difference from the controlling channel.

Each of the two autopilot actuators receive two independent electrical position commands. The signals are summed by the electrohydraulic servovalve torque motor. Error level monitoring at the summing amplifiers is used to detect servovalve and LVDT failures.

3.1.3.9 Concorde Elevon Control

The Concorde pitch control utilizes aerodynamic summing to increase flight control redundancy. There are three elevons at the trailing edge of each wing. Each elevon is operated by its own dual tandem surface power control actuator with integrated dual secondary actuators (figure 16). There are three hydraulic supplies, two that are normally connected to each dual surface power actuator plus a standby system that is switched in automatically by a pressure operated transfer valve to replace a depleted or depressurized normal system. The surface power actuators are operated in a force summed arrangement with the main valves synchronized by close manufacturing tolerances to eliminate force fight.

The actuators can be operated electrically by either of the two electrohydraulic servovalves that drive the secondary actuators or by a mechanical input lever. When the power actuator is being controlled by a secondary actuator the mechanical input is disconnected. The secondary actuators are integrated with the surface power actuators. Each secondary actuator consists of a small slide valve connected to a torque motor. The small slide valve acts as a pilot valve to one of the surface power actuator main control valves. When the small slide valve is moved by the torque motor it ports fluid to the ends of one main valve which repositions both main valves.

Damper and autopilot signals directly control the secondary actuator, hence the main valve spools and surface power actuators. The pilot's and copilot's controls have transducers that are connected directly into the autopilot electronics and provide a fly-by-wire capability through the secondary actuators. A parallel booster actuator is used to drive the mechanical control cables to keep the mechanical and electrical surface power actuator inputs in synchronization. The secondary actuators are controlled by two completely independent electrical signalling systems, one in operation and the other one in standby. In case of complete electrical control system failure, the airplane can be safely flown with mechanical control.

A monitoring system detects failures that originate in the electronics, hydraulic systems or actuators. (Figure 17) If there is an electrical failure that causes a spurious deflection of the control surface the comparator circuits switch the control to the standby electrical command path. The switching is done in two groups of surfaces comprising the inner elevons and the center and outboard elevons on each wing. For example, if an inner elevon disagreed with the other surfaces, both inner elevons would be switched to the standby command path. In case of a second failure in a group, the surfaces in that group revert to mechanical control. The other group of surfaces continues to provide autopilot control functions. There is a spring pot with a microswitch on each main servovalve to detect stuck valves. The pilot depressurizes any actuator that signals a stuck valve.

3.2

TASK 2 - SELECTION OF RECOMMENDED ACTUATION SYSTEMS

The work statement for this task required selecting two actuator configurations which explore different methods of implementing redundant actuation with applicability to the lateral axis as well as the pitch axis for an AST application.

The systems that were selected for examination and described in Task 1 are representative of secondary actuator redundancy concepts currently being used in aircraft as well as those that have been developed for specific research contracts such as the Survivable Flight Control System Development sponsored by the USAF and the NASA F-8C Fly-By-Wire Program. Actuator redundancy techniques under consideration by NASA for the Space Shuttle actuation subsystems were also included.

All except one of these systems are categorized as either force-voted or active/standby systems.

<u>Force-Voted</u>	<u>Active/Standby</u>
B2707	HRM-A
HRM-C	F-8C (primary mode)
GE 680J	Concorde
MRCA	

The one exception is the LTV electromechanical rate-summed system. It was not considered a candidate for critical flight control systems because:

- a. The complex gearing would make it difficult to prove that jam-type failures would be extremely remote
- b. For the same output force the electromechanical actuator is larger and heavier than an equivalent electrohydraulic actuator.
- c. The electronics to drive a rate-summed actuator would require a significant increase in packaging size, weight and cost. In addition the system dissipates much more power than required for an electrohydraulic force-voted actuator. (Reference 4).

It had been noted earlier in the Task 1 discussion that although position summing is a method of achieving a single valued output of a redundant actuator arrangement, none of the systems investigated employ this method either on surface actuators or secondary actuators. This type of configuration is difficult to mechanize practically for more than two channels because of the complex linkage required.

3.2.1 System Comparison

Each of the systems suitable for AST application was examined qualitatively with respect to the comparison factors discussed in Task 1.

Load Sharing

Only actuators in the force-voted category are concerned with load sharing. The secondary actuators of the force summed systems all use electronic loop closure. Since the components that make up feedback loops are essentially the same, all the systems should have the same load sharing performance.

Input Mismatch

Here again only force summed arrangements are concerned with mismatched inputs. The B2707 secondary actuators system and the HRM-C sensed the mismatch as reflected on the output in terms of differential pressure at each individual piston. An electronic signal proportional to this differential pressure is fed back as an equalization signal in each control channel, to minimize the mismatch.

The 680J and F8-C systems use no electronic feedback for equalization but depend on the low pressure gain of the single stage electrohydraulic servo valve to give the actuator a low effective spring rate. The lower the actuator spring rate, the more input mismatch can be tolerated for the same design level of load sharing. The 680J and F8-C systems are limited to the degree of input mismatch that they can accommodate because of physical pressure gain constraint. To operate within these limits, signal conditioning of input commands by means such as electronic voting is required.

The MRCA system utilized neither feedback equalization nor reduced actuator stiffness to accommodate input mismatch. Channel mismatches of up to 10 percent of full command are absorbed in force detents between each actuator and the

common output. The detent is constructed to have little effect on total system stiffness. The system does require upstream voting or some method to assure that inputs have differences of less than 10 percent.

Utilization of equalization feedback gives a great amount of flexibility to accommodate input mismatch and is probably more desirable than requiring electronic complexity upstream such as voting to insure closely matched inputs.

Failure Insensitivity

The systems applicable to an advanced SST all meet the requirements to be operational after two failures. For clarification, although the MRCA system is presently a 4-actuator configuration powered by two hydraulic supplies, additional hydraulic systems could be added to meet the fail-operational requirement.

With respect to surface transients, the force-voted systems do not rely upon the failure detection and switching to prevent transients. The magnitude of transients is governed by the structural stiffness of the mechanical linkage connecting the individual actuators. As an example, the individual actuators in the 680J system are close together and coupled by a very stiff output member. This system has almost negligible output transient.

In the active/standby systems, output transients are dependent on the failure detection threshold, switching time and the position synchronization of the standby system.

Active/standby systems such as the HRM-A type do not suffer a performance degradation after the first and second failures. Force-voted systems, however, may suffer a performance degradation after successive failures. This degradation is caused by residual force fight between channels and reduced system force capability.

Failure Detection Capability

By design, none of the force-voted systems requires a failure detection capability to keep the system safe for the first failure. As long as there is a majority of healthy channels the voting system disregards a failed channel. The failure detection system must, however, isolate the failed channel within a time consistent with the probabilities of a second failure.

All of the force voted systems except the MRCA use the differential pressure generated across each individual actuator as the source of failed channel logic. The MRCA senses motion of the mechanical detent associated with each actuator. Since immediate detection of a failure is not critical for safety, the failure detection logic can employ a reasonable threshold and time delay.

In systems such as the B2707 the equalization feedback, which is used to minimize effects of input mismatch, degrades the failure detection capability. Some failures such as ramps can be equalized and therefore masked from detection.

Failure detection capability in an active/standby system is critical to the success of the system concept since the detection of failures and switching to standby is necessary to be safe. The threshold of detection and the associated switching time are set by the allowable surface transients for a given application and must be significantly smaller than those that can be allowed in a force-voted system. These small thresholds make the active/standby system vulnerable to inadvertent disconnects.

Reliability

Reliability is related to the number of components. Those systems that utilize separate electromechanical monitors for each of the three working channels such as the HRM-A and HRM-C use fewer working channels. Trading the complexity of three monitors for one additional working channel impacts the overall system reliability. If each control channel is duplicated with a monitor, the probability of that channel or its monitor failing is doubled. A three channel monitored system would fail down to a monitored single channel operation twice as often as a four channel system would fail down to two channels.

Self Test Capability

None of the systems examined had specific ability to perform a self test within the actuator loop, however, each possessed the necessary sensors to provide logic for self test mechanization.

Simplicity

In general, the four channel force-voted actuation systems appear simpler than the three channel systems with monitors. However, the upstream signal voting and/or channel equalization electronics increase the complexity of the force-voted systems to narrow the difference and make relative simplicity difficult to judge without further study.

3.2.2 System Selection

Examination of the force-voted systems shows little difference in fundamental mechanization. The most significant difference is the use of equalization to minimize the effects of input mismatch as in the B2707 system and the operation without equalization as in the 680J system. This difference is a function of the electronics driving the systems. The B2707 used an unvoted analog system which had a susceptibility to accumulation of tolerances resulting in significant command mismatch. The 680J also is driven by an analog electronic system but one which has a monitored voting stage just prior to the actuator, thereby guarantying a single valued input to the actuators. The requirement for equalization in the actuator is therefore eliminated and the failure detection covers only failure within the actuator loop.

There is little difference in the active/standby systems examined. The HRM-A remains an active/standby as the system fails down to single channel. The F8-C system is a hybrid system since it fails down to a three channel force-voted system after the first failure. The Concorde system is a two channel system but achieves overall fail operational capability for many dual failures by use of multiple aerodynamic surfaces (6 elevons) and voting between pairs of surfaces.

While there is little difference in the variations of either force-voted or active/standby systems there are significant philosophical differences between the two categories.

Failure Detection

The active/standby concept requires failure detection to be safe following failures. The force-voted concept does not require immediate detection of a failure to be safe. Failure detection is only required to enable a failed channel to be shut down before another failure occurs.

Switching

The standby system must be continually monitored to assure that it is capable of control if the active channel fails. Further, somewhere in the system a device like a switch or blocking valve is required to operate without prior knowledge of its health to provide a successful switch to standby. The force-voted system is comprised of only active channels continually monitoring each other requiring no switching.

Performance After Failure

The active/standby concept preserves normal performance as it fails down from active to standby to second standby. The force-voted system may suffer a performance degradation as it fails down. This degradation can be exhibited in poorer resolution and limited force output.

Either of these two concepts can be mechanized to meet the redundancy requirements for an advanced supersonic transport but the philosophical differences in the approach to redundancy warrant further study.

A force-voted configuration should be mechanized in a manner similar to the schematic shown in figure 18. The actuator is a four channel, force-voted electrohydraulic position servo. The four independently controlled actuator channels are coupled to a common output. Each actuator has a LVDT to provide position feedback to its flight control channel. The differential pressure sensor and bypass valve limit the maximum differential pressure and provide an electrical signal proportional to the differential pressure which can be used for cross channel monitoring and equalization. The actuator differential pressure sensor could be a pressure transducer that signals a solenoid operated bypass valve. The modular nature of the side-by-side design is such that studies could be performed with fewer or a greater number of actuator elements.

A schematic of a proposed active/standby study configuration is shown in figure 19. The actuator is a three channel active/standby position servo employing monitor channels. One channel (number 1) is engaged for normal operation. With a malfunction in the controlling system, a switch is made to a standby system and there is no loss in output force or performance. If a malfunction occurs in system 2 a switchover to system 3 will be accomplished in a similar manner. If system 2 has failed before system 1, failure of system 1 will cause a switchover to system 3. In this configuration, only a channel that is operational is capable of gaining control of the actuator output.

The failure sensing and switching are electronic rather than hydraulic to allow a greater latitude for experimentation with failure detection levels and switching times. The actuator can also be arranged with identical modules side-by-side to allow flexibility in the number of actuator elements under test.

TASK 3. FORMULATION OF MATH MODELS OF THE RECOMMENDED SYSTEMS

Math models of the recommended systems have been formulated. These models are in such a form that they may be adapted for piloted simulator evaluations using analog and/or digital simulation techniques. The math models include all the functions required so that the following items may be studied:

- o Normal performance
- o Performance after failure
- o Channel equalization
- o Failure and switching transients
- o Failure detection logic
- o Critical overload due to aerodynamic hinge moments
- o Static stiffness as a function of the number of hydraulic systems operating
- o Feedback malfunctions

The math model of the force voted system is shown in figures 20 and 21. Table 1 gives nominal parametric data which will give an actuator representation with adequate output force and performance for use in either pitch or roll control. The details of the failure detection and equalization box are shown in figure 21. The parametric values for the failure detection and equalization network must be developed to be compatible with the airplane and airplane control axis that the system is used on. Therefore no values have been given.

The math model of the active/standby system is shown in figure 22. The parametric data, except the failure detection level, to construct a nominal actuator representation is given in table 1. The failure detection level must be set after the model is matched to an airplane system. The math models were checked by using the models to write the differential equations of the system. The equations were solved for performance characteristics. Application of stability criteria showed that the actuators would be stable. All solutions provided answers that correlated well with previous analyses and data obtained by testing actual hardware. These equations were then checked by dimensional analysis in both US units and SI units.

Because of the similarity of the systems and the math models to others previously simulated without difficulty, computer simulation would not add to the confidence in the models gained by paper analysis. Therefore computer simulation that had been previously planned was not used for verification.

In order to utilize the math models of the secondary actuators in a piloted simulation, the actuators must be included in a simulation that represents the surface power actuators and an airplane. A math model of a surface power actuator that would be compatible with the secondary actuator models that have been presented is shown in figure 23. The surface power actuator model is sensitive to aerodynamic hinge moments and changes in hydraulic pressure. For maximum realism the airplane model used in conjunction with the actuator model should be one that contains surface hinge moment data.

TASK 4. LONG RANGE PLANNING FOR REDUNDANT ACTUATION
DEVELOPMENT

The draft for the Statement of Work for Phase II is presented below.

A. SUMMARY

Large gains in supersonic airplane performance and economy are achievable through the use of advanced flight control systems. As the advanced large supersonic cruise transport must take advantage of these gains, it is essential to fully understand and appreciate the implementation of these advanced control systems. The use of active controls makes this technology transferrable to other classes of aircraft.

This program, to develop multiple redundant actuation concepts and associated hardware required for the advanced SST flight control system, has accomplished under Phase I, (1) a review of recent developments in redundant control systems, (2) the selection of the two most probable candidate redundant actuator concepts, and (3) the construction of math models of the two selected configurations.

The two actuator configurations selected are a four channel force-voted system and a three channel active/standby system.

The force voted configuration is similar to both the Boeing SST Horizontal Stabilizer Electric Command Actuator and the Secondary Actuator developed by General Electric for the Air Force Flight Dynamics Laboratory's F-r Survivable Flight Control System.

The active/standby configuration is similar to the secondary actuator developed by Hydraulic Research and Manufacturing Company for the NASA Manned Spacecraft Center's Project Space Shuttle.

Under Phase II of this same program, these candidate systems are to be further investigated and evaluated to (1) formulate the basic knowledge and experience needed of the operational and performance characteristics of these concepts to establish a technology base for mechanizing advanced flight control systems, and (2) to define a research tool to be used in conjunction with an ARC simulator to allow a genuine determination of system

performance, handling qualities effects, and various failure modes with flight crew interaction and simulated airplane response.

B. WORK STATEMENT

The proposed Phase II study of redundant actuation will be divided into five tasks. The statement of work for each task is as follows.

1. Task 1 - Configuration Definition of Redundant Actuator Concepts

The Phase I study that determined the system concepts to be further studied in this phase emphasized the basic requirements for redundant control systems. The two concepts are to be implemented in such a manner that they will:

- o Meet normal performance requirements
- o Have limited interchannel force fight
- o Be tolerant of input mismatch
- o Operate after first and second failures
- o Operate at reduced redundancy levels
- o Allow failure monitoring
- o Have self test capability

The analysis in this task will produce a detail design definition of the two actuator system concepts and will provide quantitative assessment of their practicality for the AST airplane design with consideration given to scaling of important parameters to other aircraft. The factors to be considered are all of those stated above, plus failure induced transients, load sharing after failure, stability of the basic system before and after failure, filtering requirements, the need for mechanical backup to the electric command mode of operation, and delay time to regain control after failure.

2. Task 2 - AST Actuation System Requirements

The B2707-300 pitch axis configuration as currently mechanized in the ARC simulation will be used to establish parametric data needed for actuation system development. The configuration sensitive parameters such as rate of signal input, dynamic response, resolution, and airplane tolerance to failure transients will be determined to formulate the actuation system design requirements.

3. Task 3 - Computer Simulation of Redundancy Concepts

The purpose of this simulation is to define the nominal design parameters to be used in the design of the single axis mini-rig. This requires a motion simulation with a pilot. To fulfill this requirement the contractor will furnish a detailed math model of the two actuation systems.

ARC will then implement the math models on the simulator. The contractor will submit a test plan for simulator checkout procedure and to gather mini-rig design parameters. The test plan will include a time schedule and pilot requirements. The contractor will perform the test at ARC with appropriate ARC support.

4. Task 4 - Mini-Rig Definition

The extent of the flight control system required to be represented by the mini-rig will be determined. Based in part on the successful operation of the computer simulation of the AST and control systems implemented in Task 3, the advisability of providing a mini-rig for both actuation system concepts will be determined. The mini-rig will be limited to the representation of the secondary actuator system and associated electronics with the surface actuators remaining part of the computer simulation. The secondary actuators will be manufactured to full scale reflecting airplane actuator quality and performance but retaining the flexibility required for the planned test program.

The feasibility of using one universal rig or a separate rig for each redundancy concept will be considered. If two dedicated mini-rigs are used, consideration will be given to assure the ability to directly compare results from both rigs. Data requirements such as FSAA and computer interface, scaling, instrumentation requirements, hydraulic and electrical system power requirements, and other relevant constraints will be specified by the contractor. A mini-rig design specification for each concept will be prepared to allow completion of a mini-rig design and fabrication and will contain at least the following:

- a. Appropriate construction and material specifications

- b. System functional description
- c. Detail performance requirements including range of adjustments on critical parameters
- d. Safety requirements
- e. Appropriate quality assurance provisions
- f. General acceptance test procedures

5. Task 5 - Planning for Mini-Rig Design Fabrication and Usage

- a. A plan will be formulated, in conjunction with ARC, for mini-rig design and fabrication.
- b. The contractor will provide a descriptive document of the mini-rig's operational capabilities.
- c. The contractor will provide a recommended test plan to investigate design problems relating to AST flight control actuation.

C. PROGRAM SCHEDULE

The recommended schedule for accomplishing the Phase II work statement is shown in figure 24.

CONCLUSIONS

Advanced airplanes will need to use redundant flight control actuators to achieve reliability approaching that of the basic airplane because operational flight controls will be essential for safe flight and acceptable airplane handling qualities.

Surface restraint to meet the fail safe requirements for flutter prevention will dictate the minimum redundancy levels allowable for control surface power actuators. Airplanes with redundant flight control surfaces may have dual surface power actuators if a third hydraulic system is provided. Control surfaces that are critical for control functions will require at least three actuators per surface in order to meet FAA requirements and provide an adequate level of safety.

Reliability requirements for actuators that amplify autopilot, stability augmentation and pilot commands to provide inputs to the control surfaces are determined by the need to operate in spite of control signal malfunctions. Actuation systems with fault corrective capability that will meet the system reliability requirements and satisfy FAA regulations require at least four active channels or three monitored channels. Surface power actuators could be mechanized with this level of redundancy but it has been found to be more efficient to utilize small secondary actuators to provide a reliable single input to the surface power actuators.

Based on a review and examination of current redundant actuation systems, two concepts were found to be representative of secondary actuator mechanization which would meet advanced airplane flight control system requirements. Both of these systems should be studied by NASA since they reflect different design philosophies. The two actuator configurations are a four-channel force-voted system and a three-channel active/standby system.

Redundant control systems have operating and failure characteristics that are affected by system design and that interact with the pilot and the airplane in which they are installed. Redundant actuators should be studied in conjunction with a pilot and an AST airplane to understand pilot reaction and airplane response to variations in control system characteristics and failures. NASA Ames has a facility that is well suited to pilot-control system-airplane studies in the FSAA. Use of the FSAA to study redundant actuator mechanization will gain technical knowledge that will benefit future advanced airplane designs.

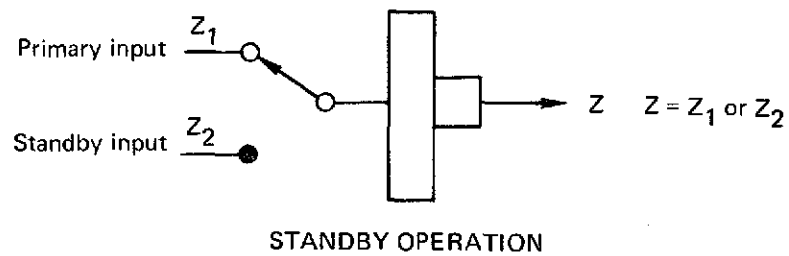
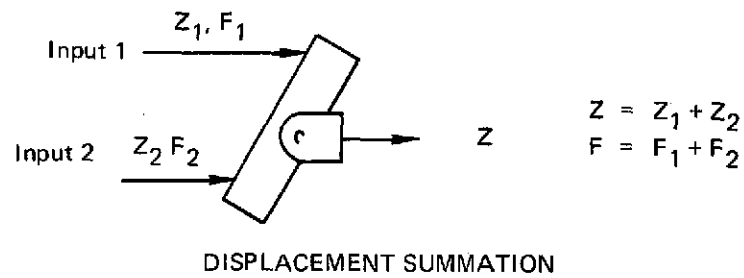
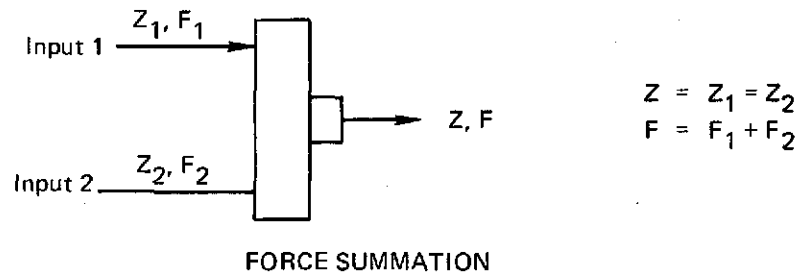


FIGURE 1.—MULTIPLE OUTPUT UTILIZATION

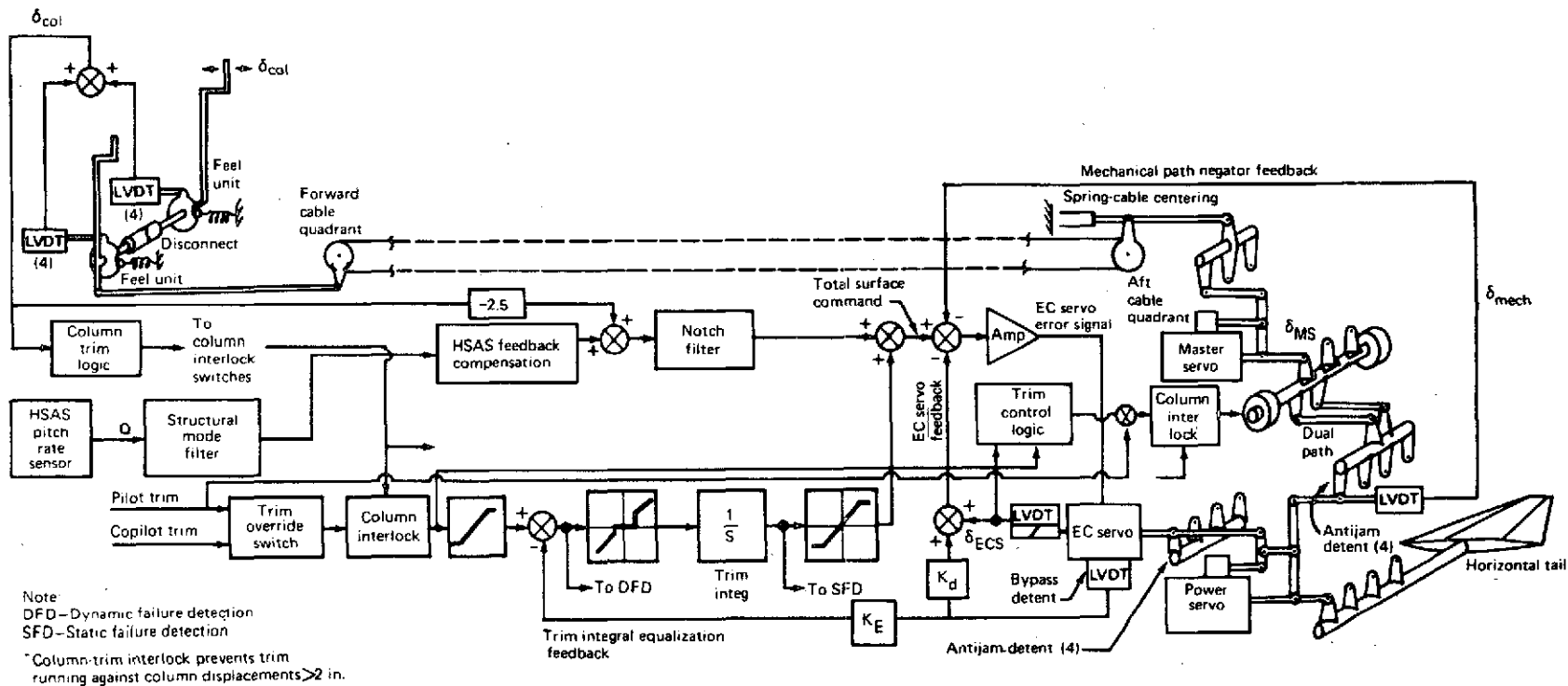


FIGURE 2.—BOEING SST HORIZONTAL STABILIZER ACTUATION SYSTEM

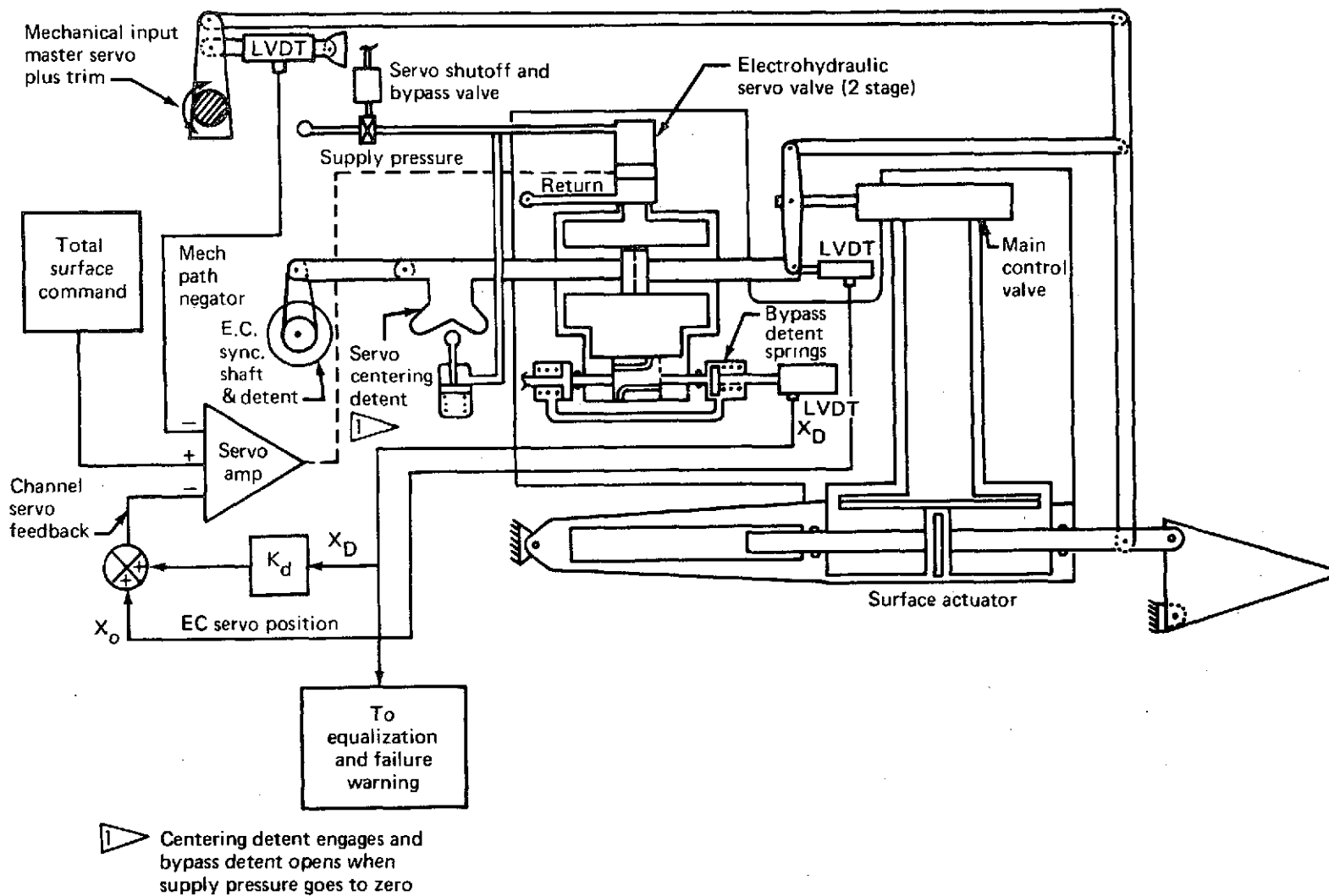


FIGURE 3.—FUNCTIONAL SCHEMATIC OF SECONDARY ACTUATOR INTEGRATED WITH THE SURFACE POWER CONTROL ACTUATOR

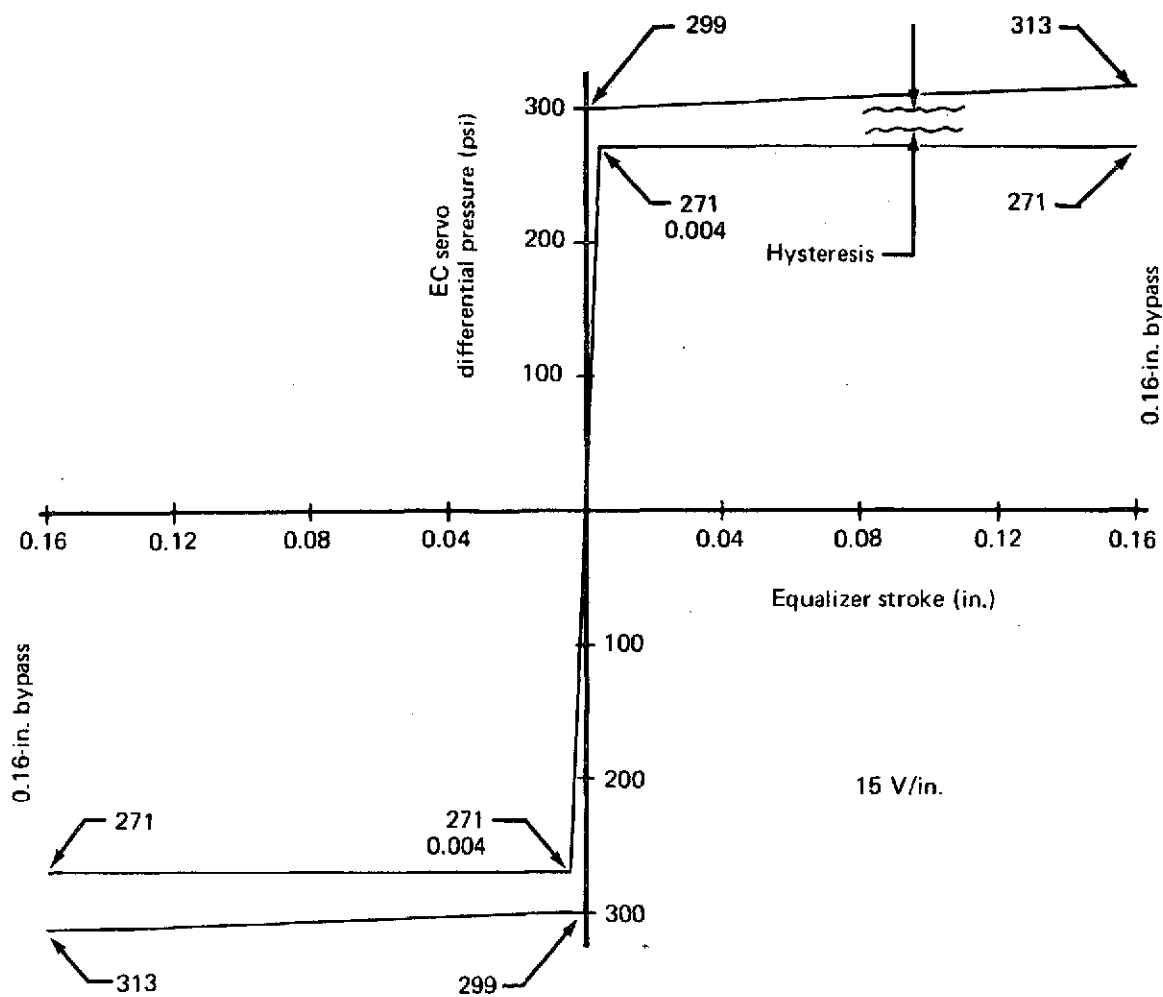


FIGURE 4.—MOTION VS DIFFERENTIAL PRESSURE FOR BYPASS DETENT

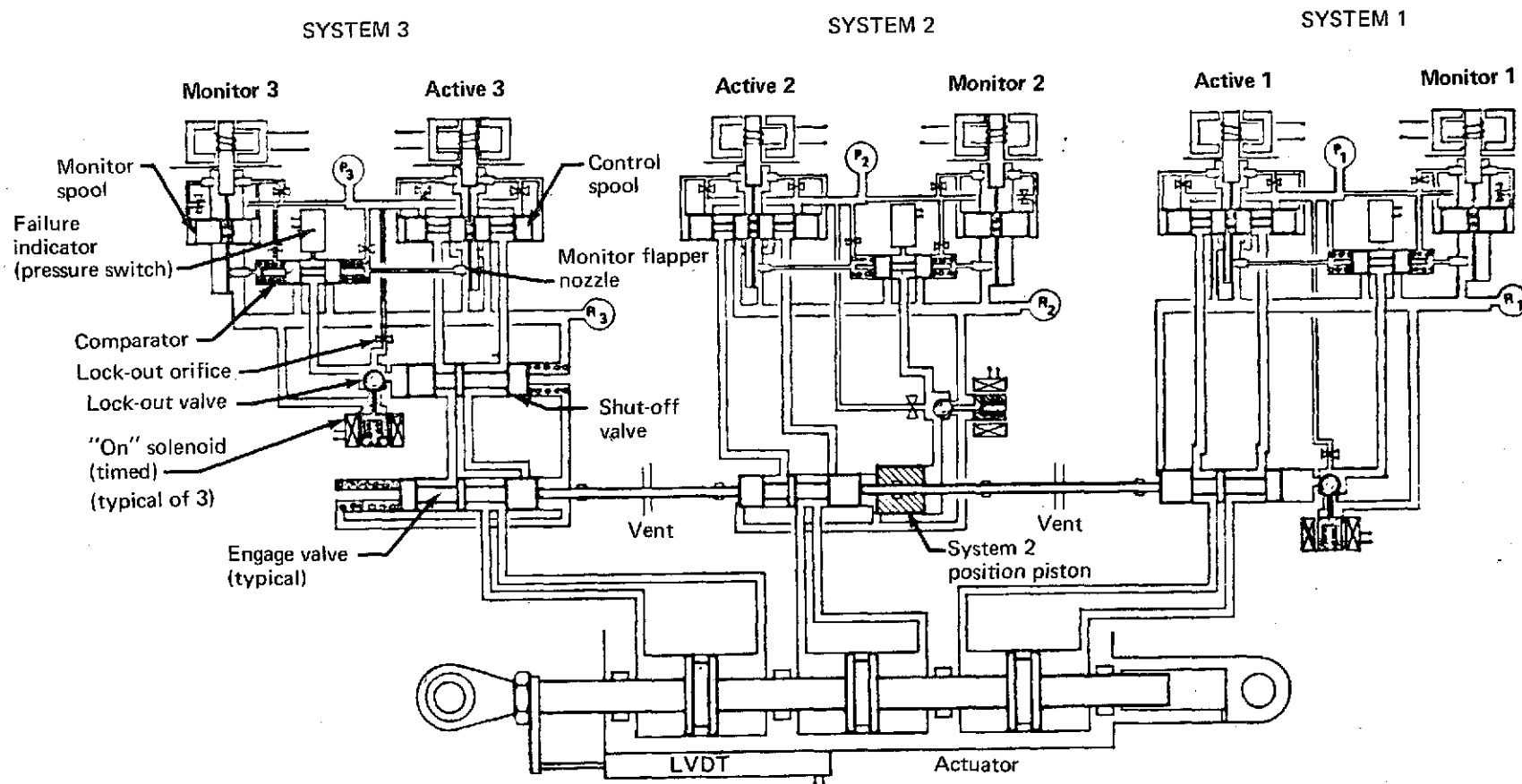


FIGURE 5.—HRM-A SECONDARY ACTUATOR HYDRAULIC SCHEMATIC

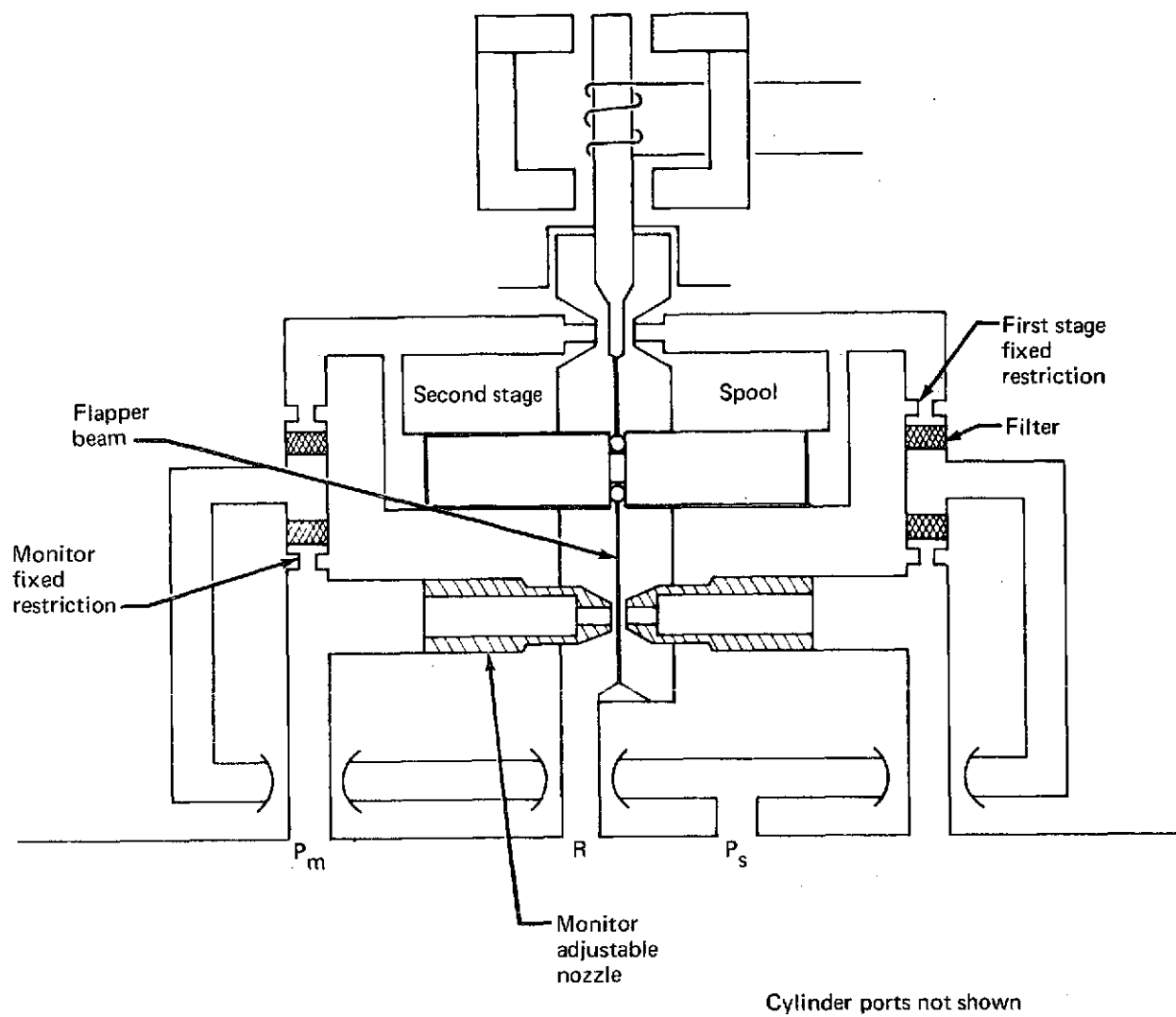


FIGURE 6. —HYDRAULIC LOGIC SERVOVALVE SCHEMATIC

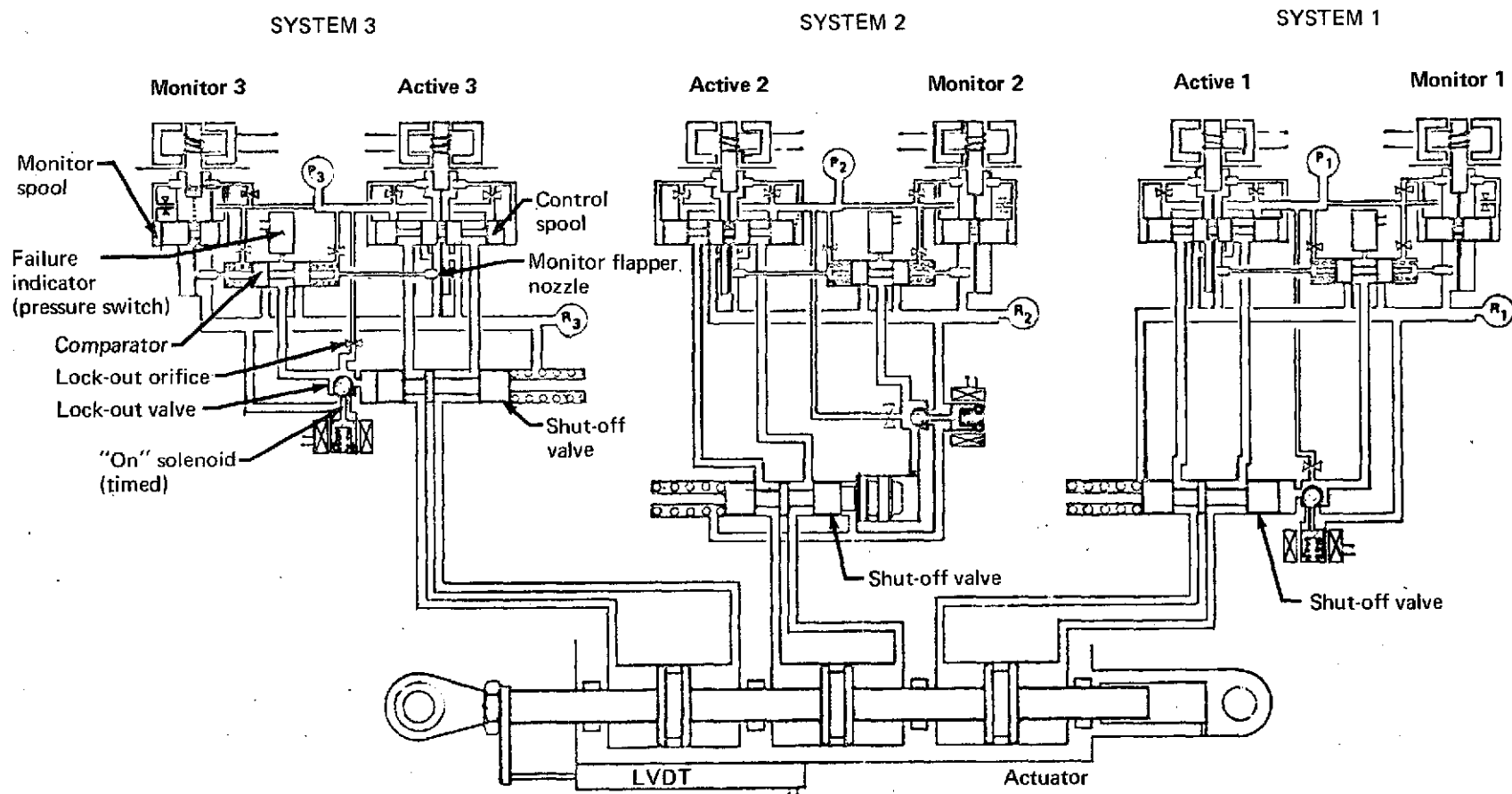


FIGURE 7.—HRM-C SECONDARY ACTUATOR HYDRAULIC SCHEMATIC

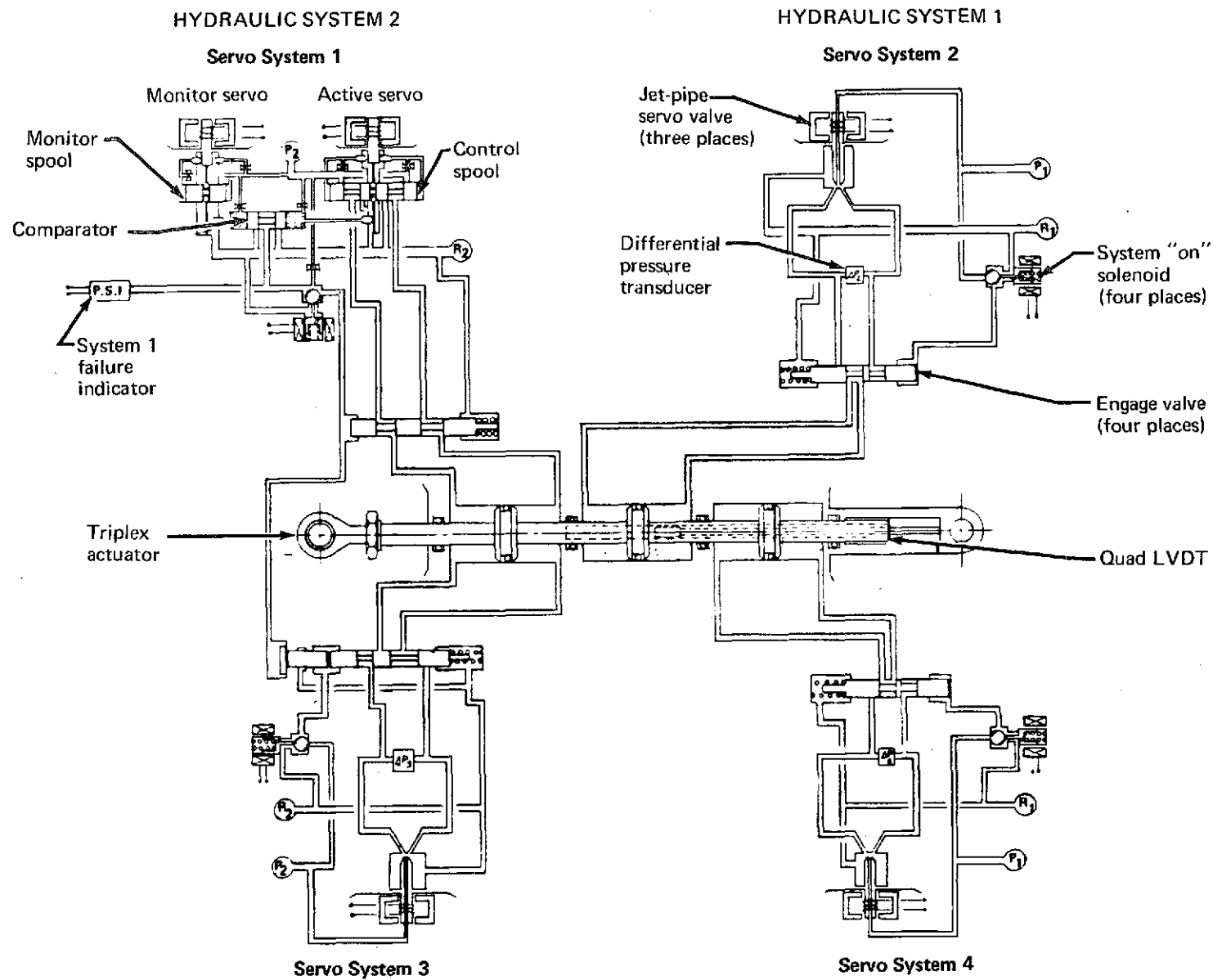


FIGURE 8. -F-8 SECONDARY ACTUATOR HYDRAULIC SCHEMATIC

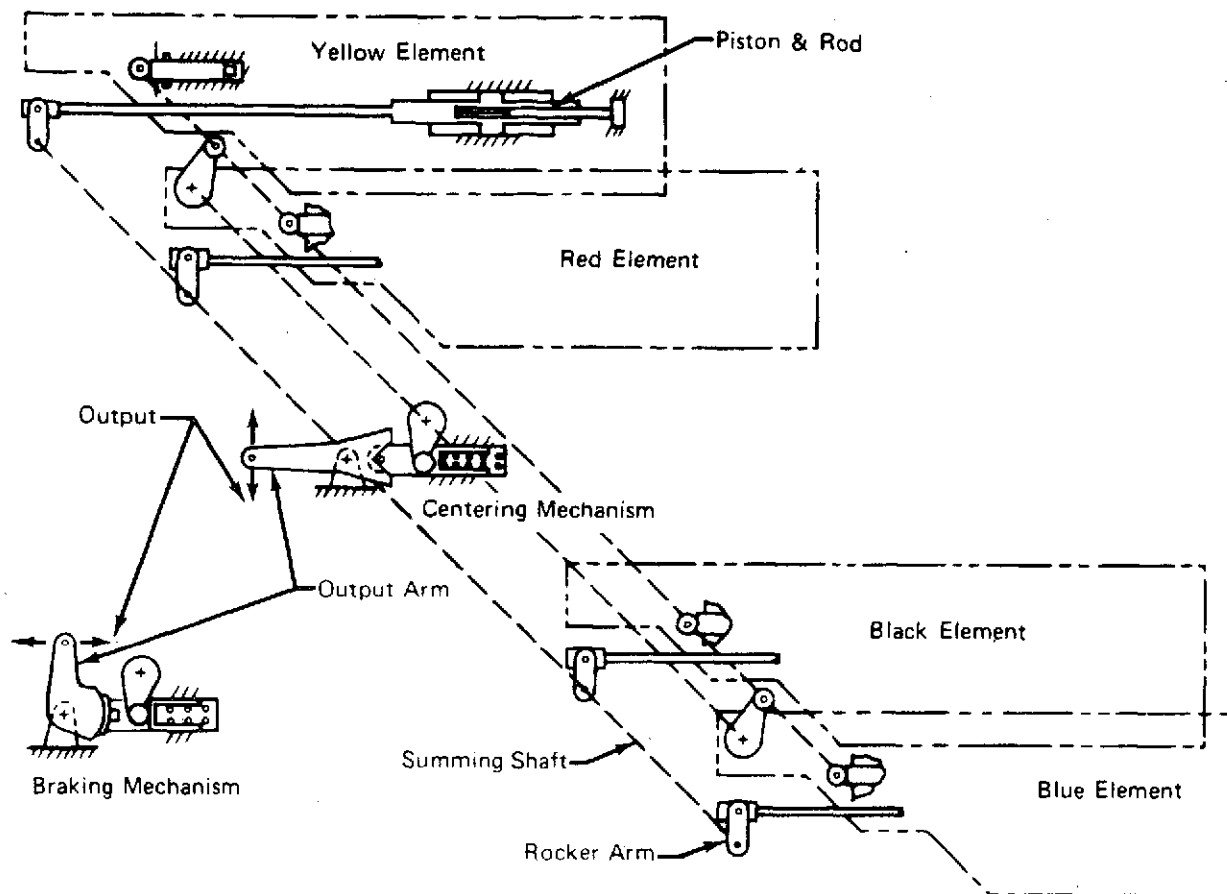


FIGURE 9.—MECHANICAL SCHEMATIC, SECONDARY ACTUATOR SUMMING

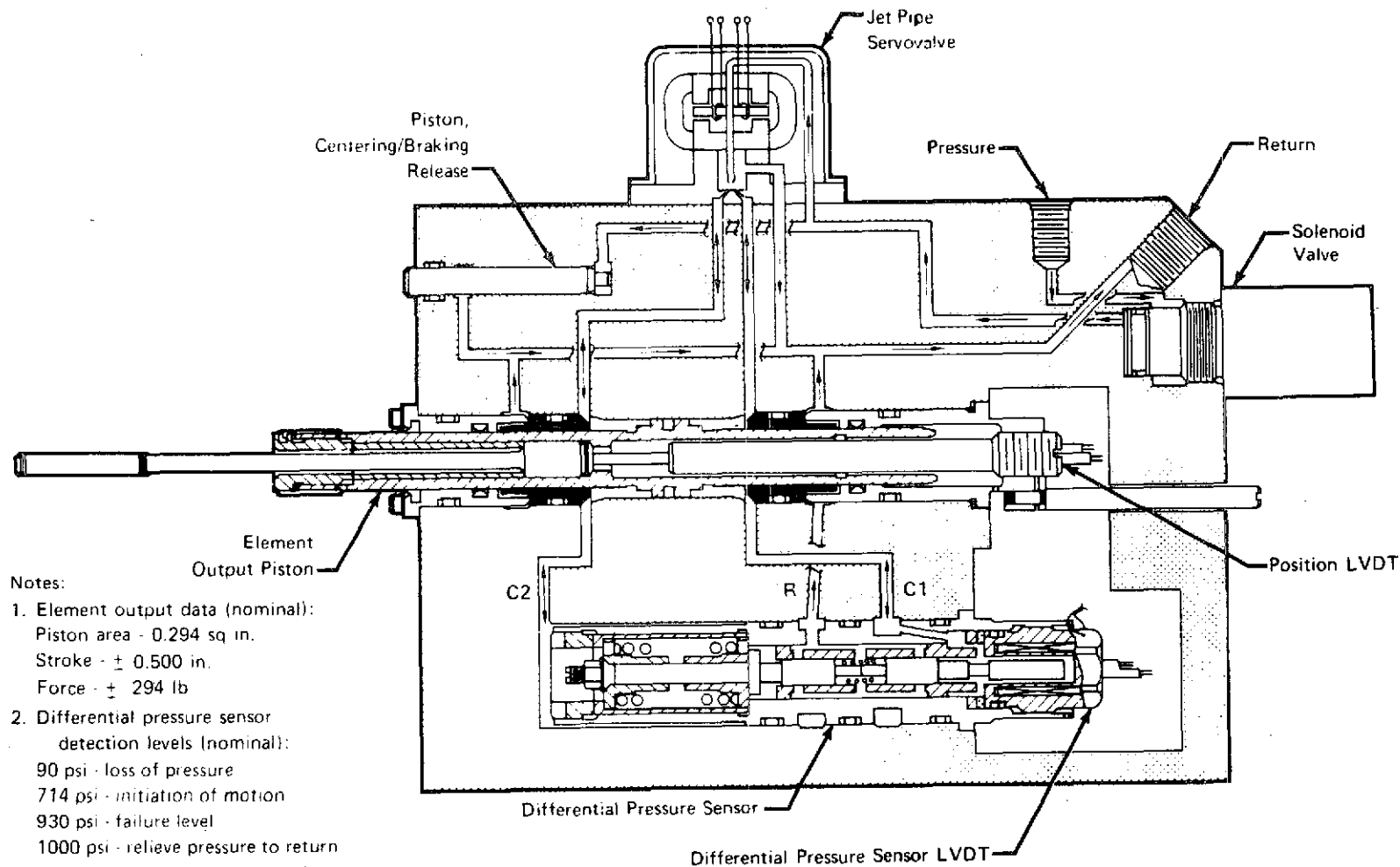


FIGURE 10.—HYDRAULIC SCHEMATIC, SINGLE ACTUATOR ELEMENT

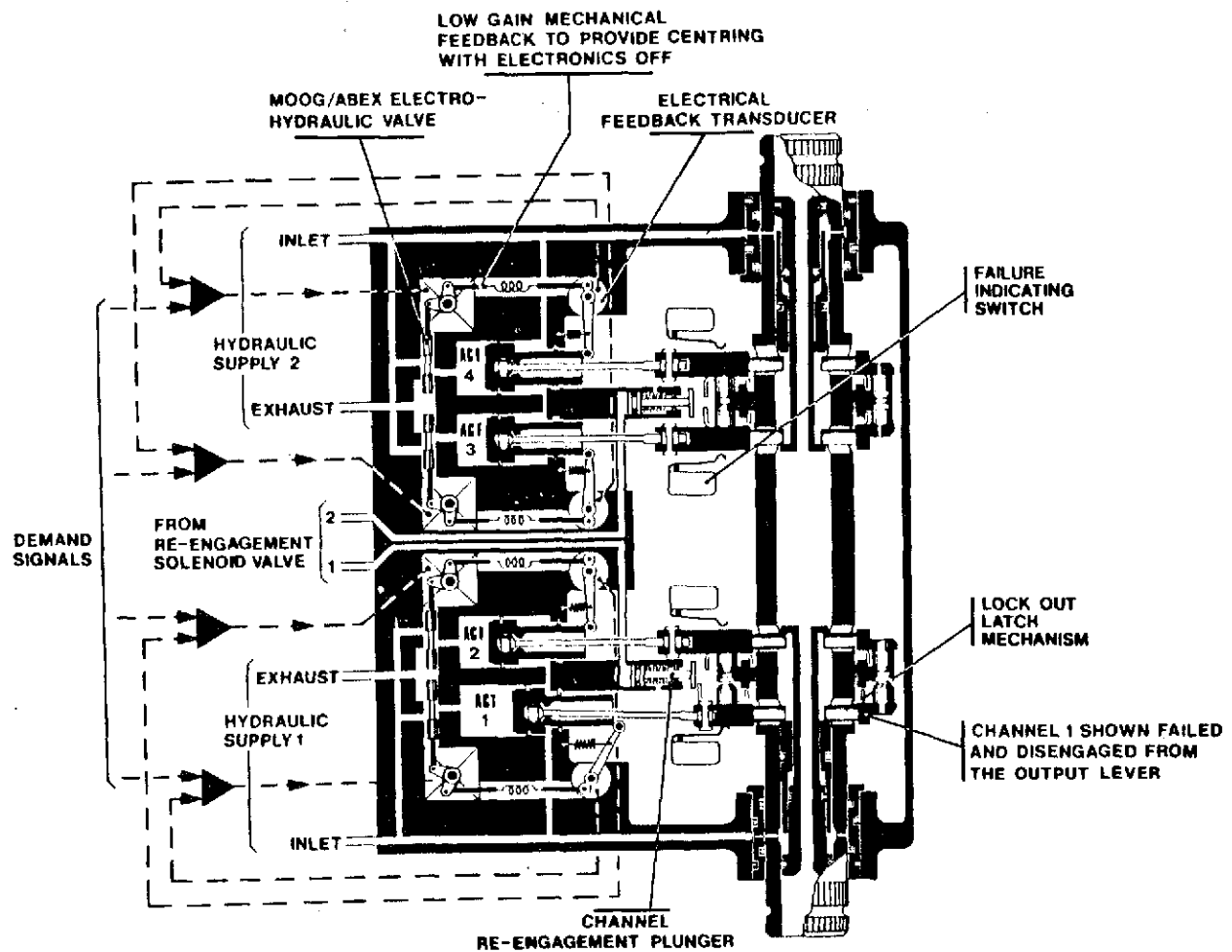


FIGURE 11.—MRCA SECONDARY ACTUATOR

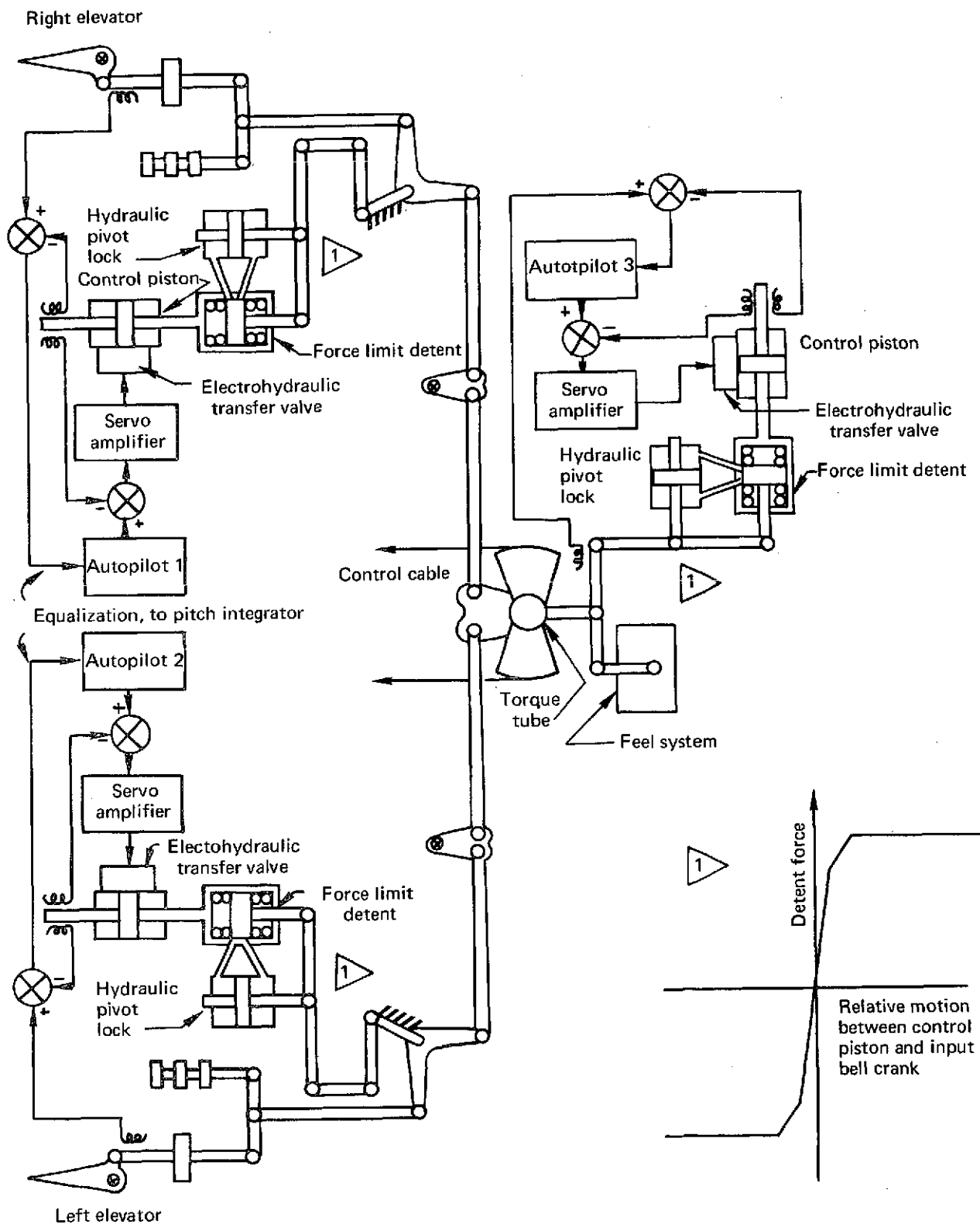


FIGURE 12.-747 TRIPLE-PITCH CHANNEL CONFIGURATION

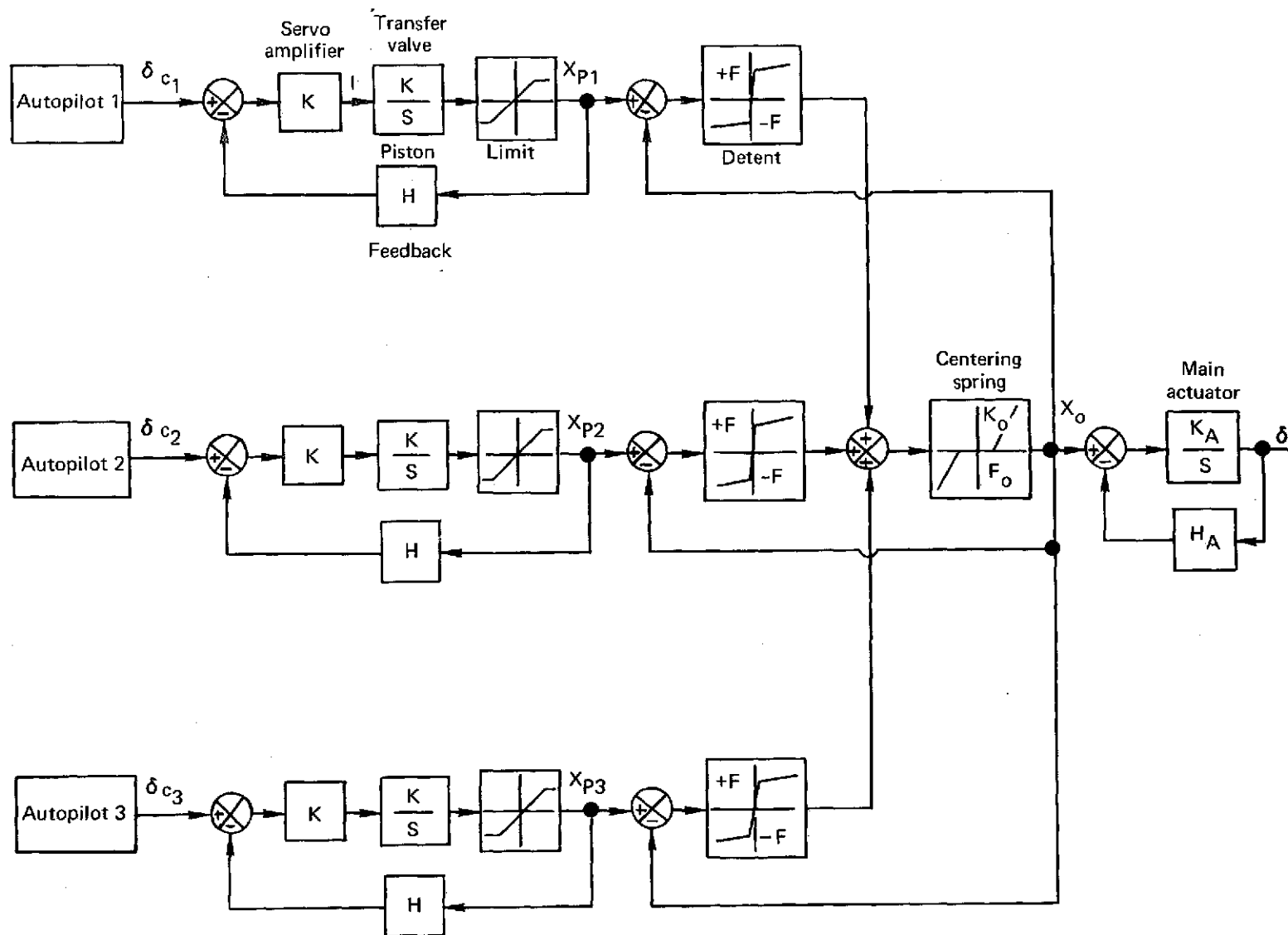


FIGURE 13.—SIMPLIFIED BLOCK DIAGRAM OF 747 TRIPLE MID VALUE VOTER

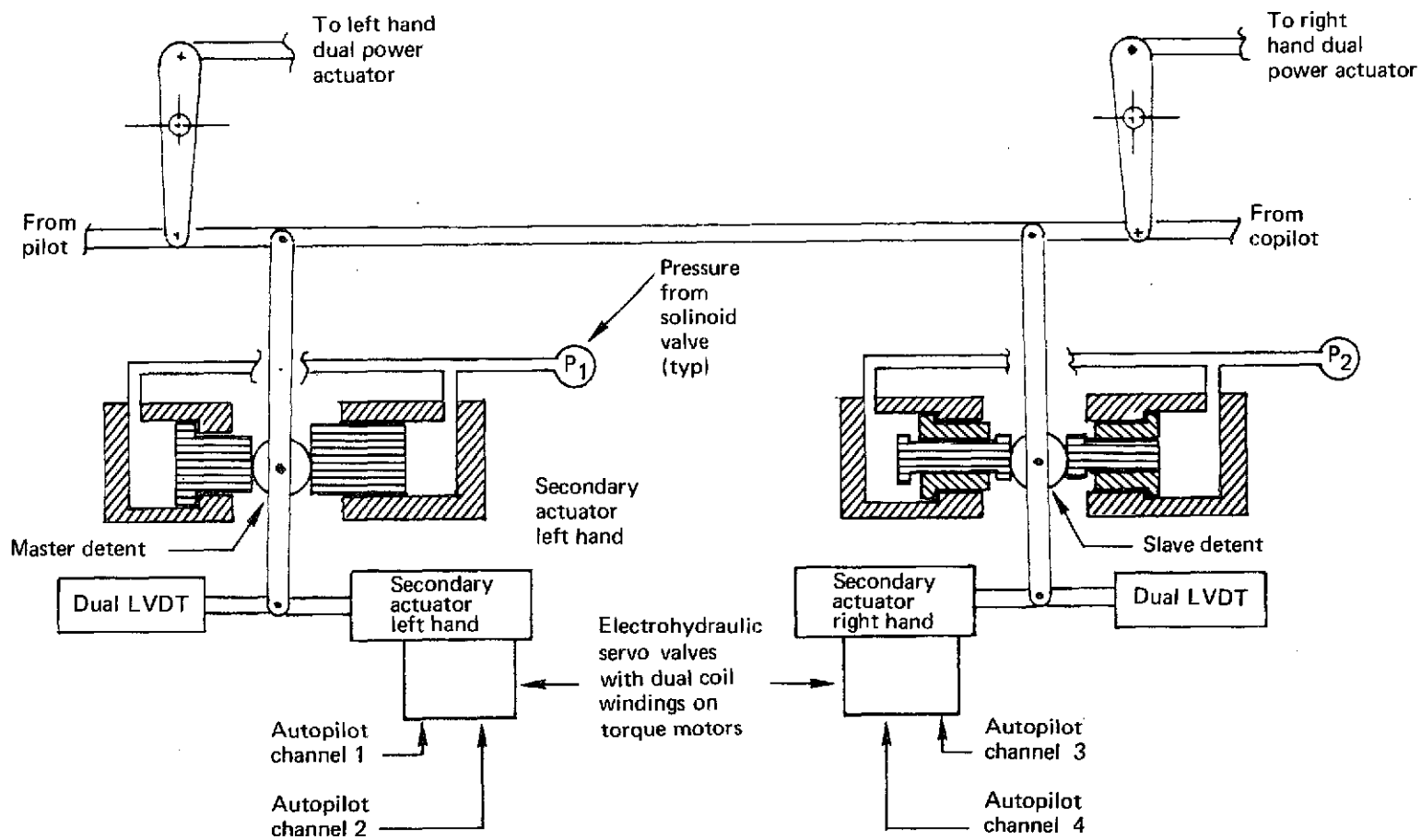


FIGURE 14.—L1011 DUAL SECONDARY ACTUATOR

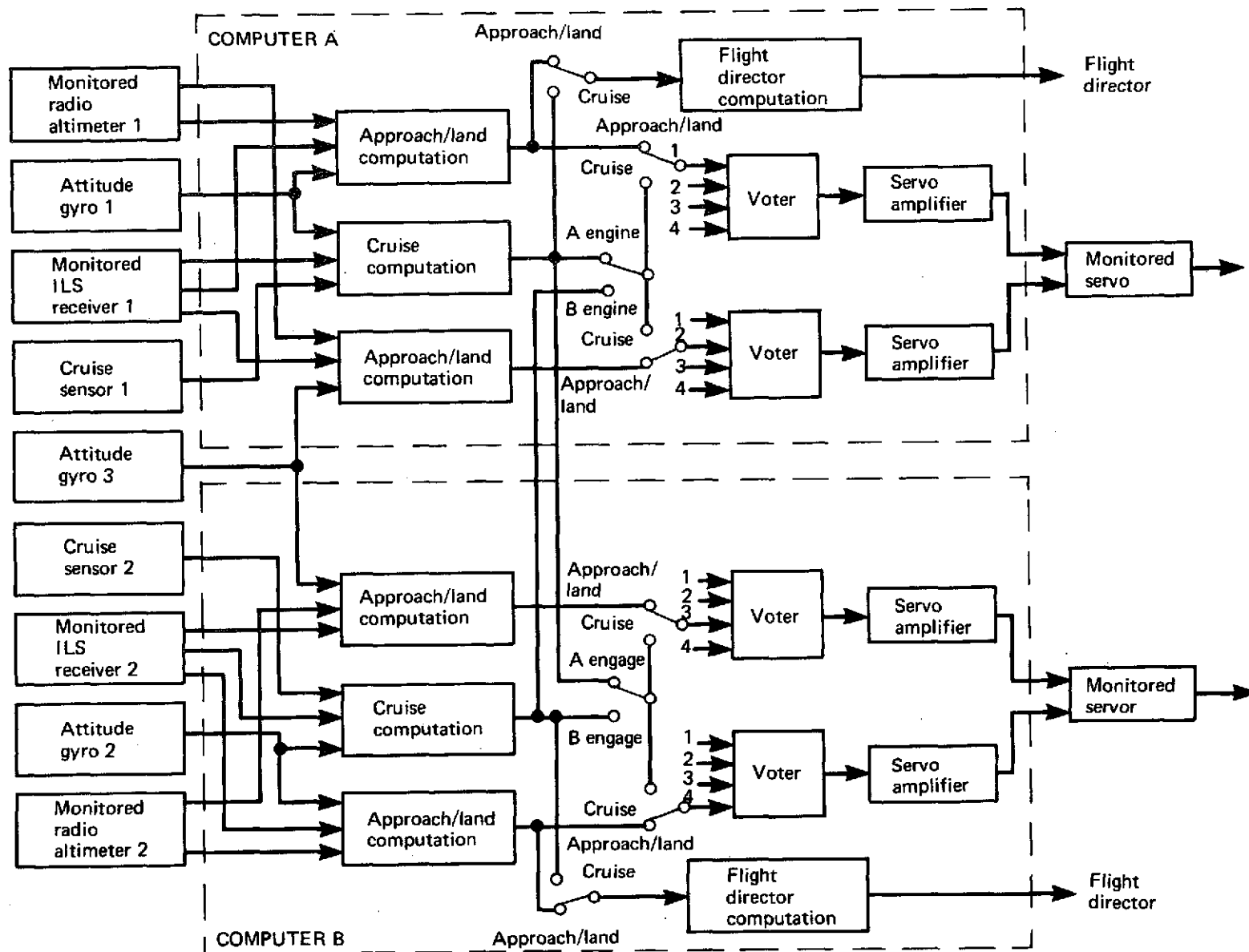


FIGURE 15.—L-1011 ROLL AND PITCH BLOCK DIAGRAM

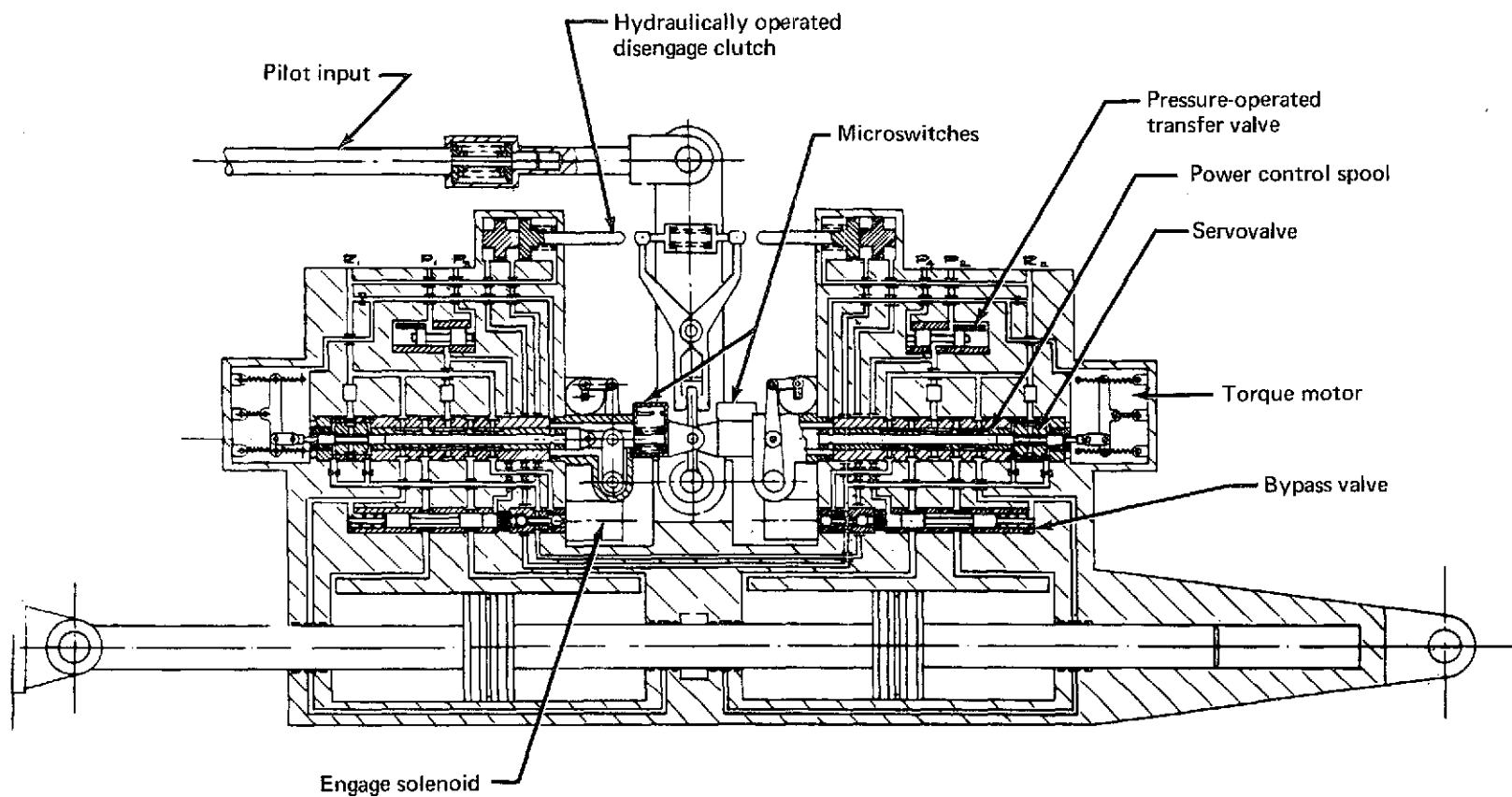


FIGURE 16.—CONCORDE DUAL ACTUATOR

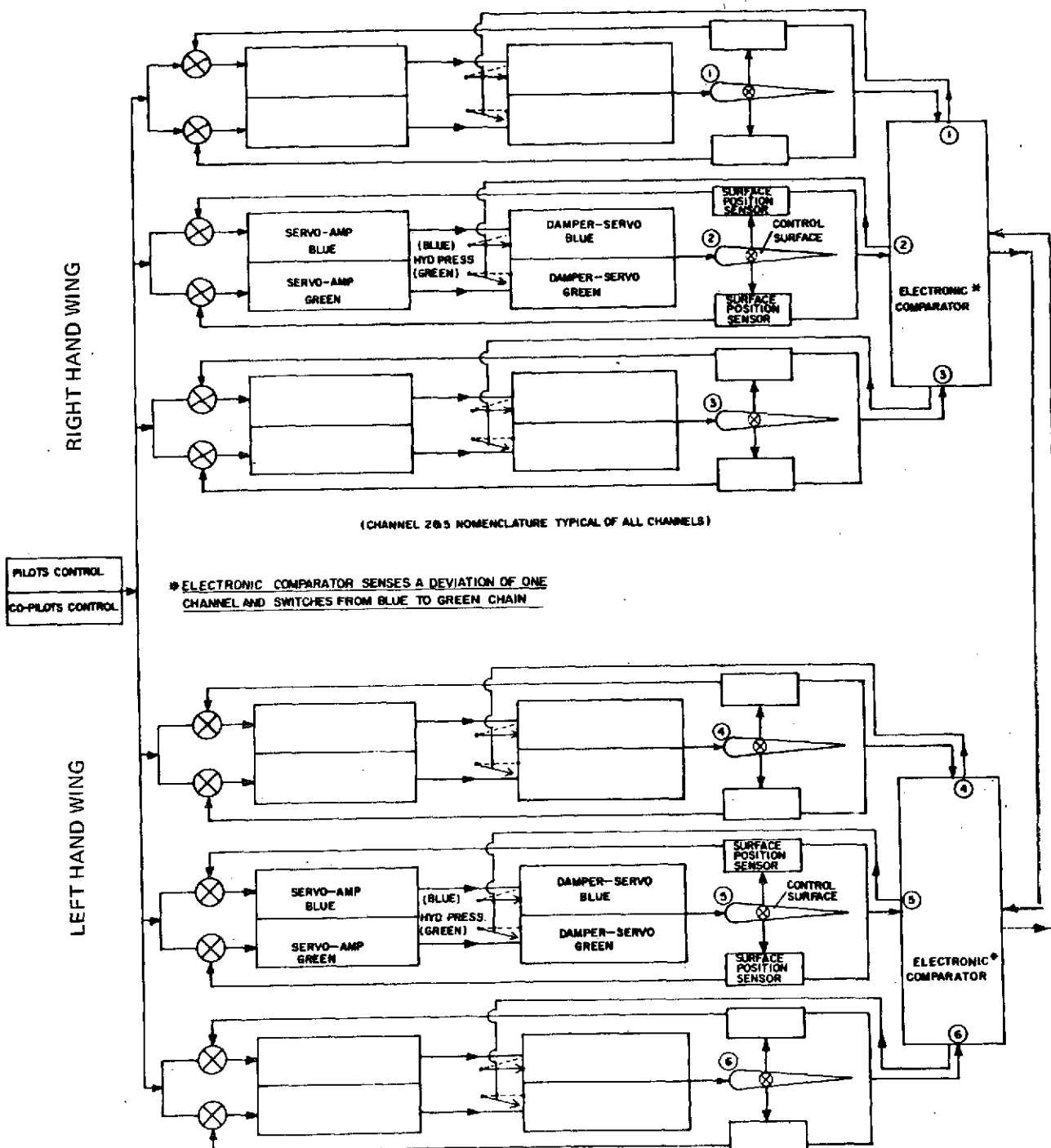


FIGURE 17.—CONCORDE ELEVON CONTROLS—OUTER LOOP MONITORING
FUNCTIONAL DIAGRAM

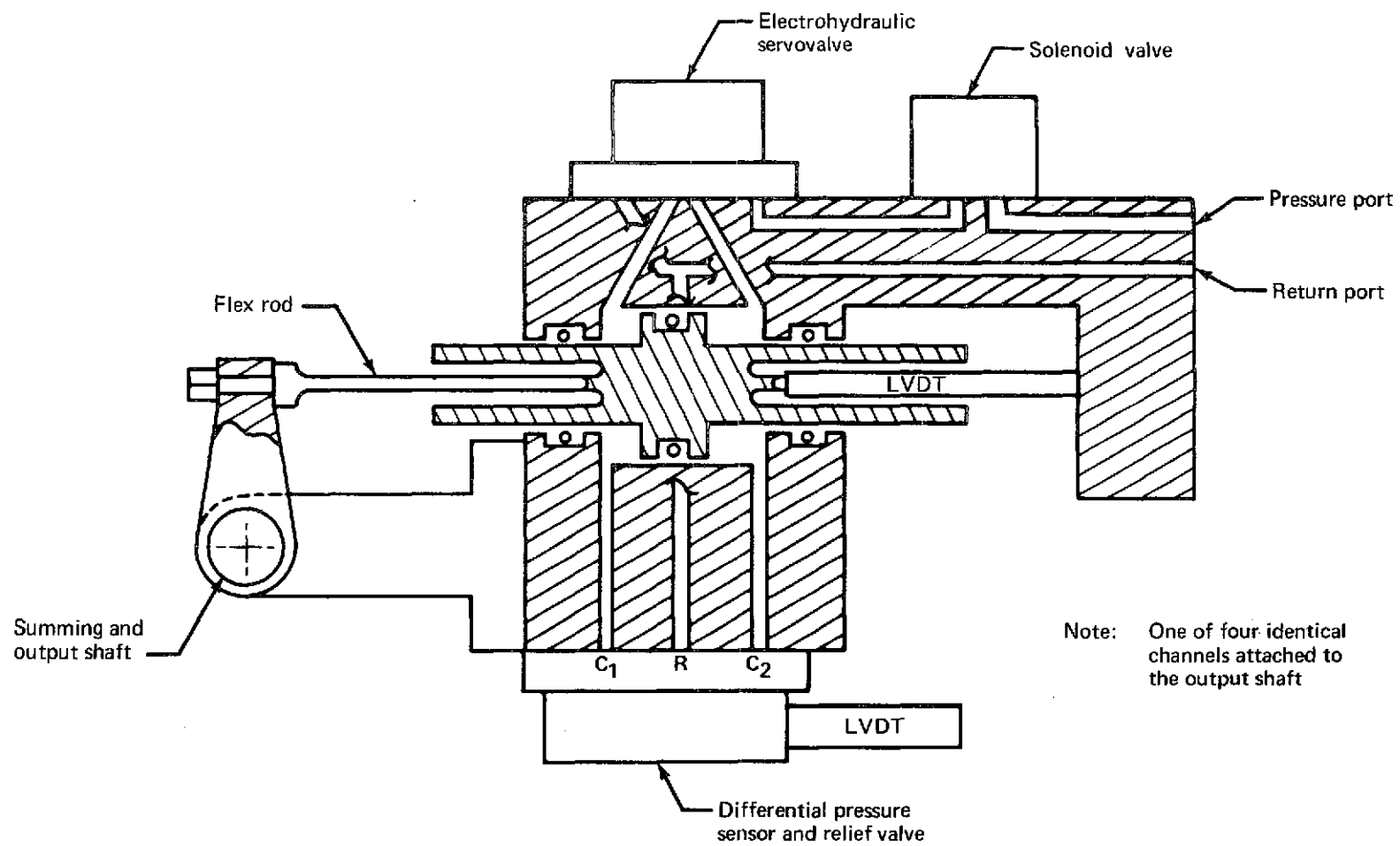


FIGURE 18.—FORCE-VOTED SECONDARY ACTUATOR, SINGLE ACTUATOR ELEMENT

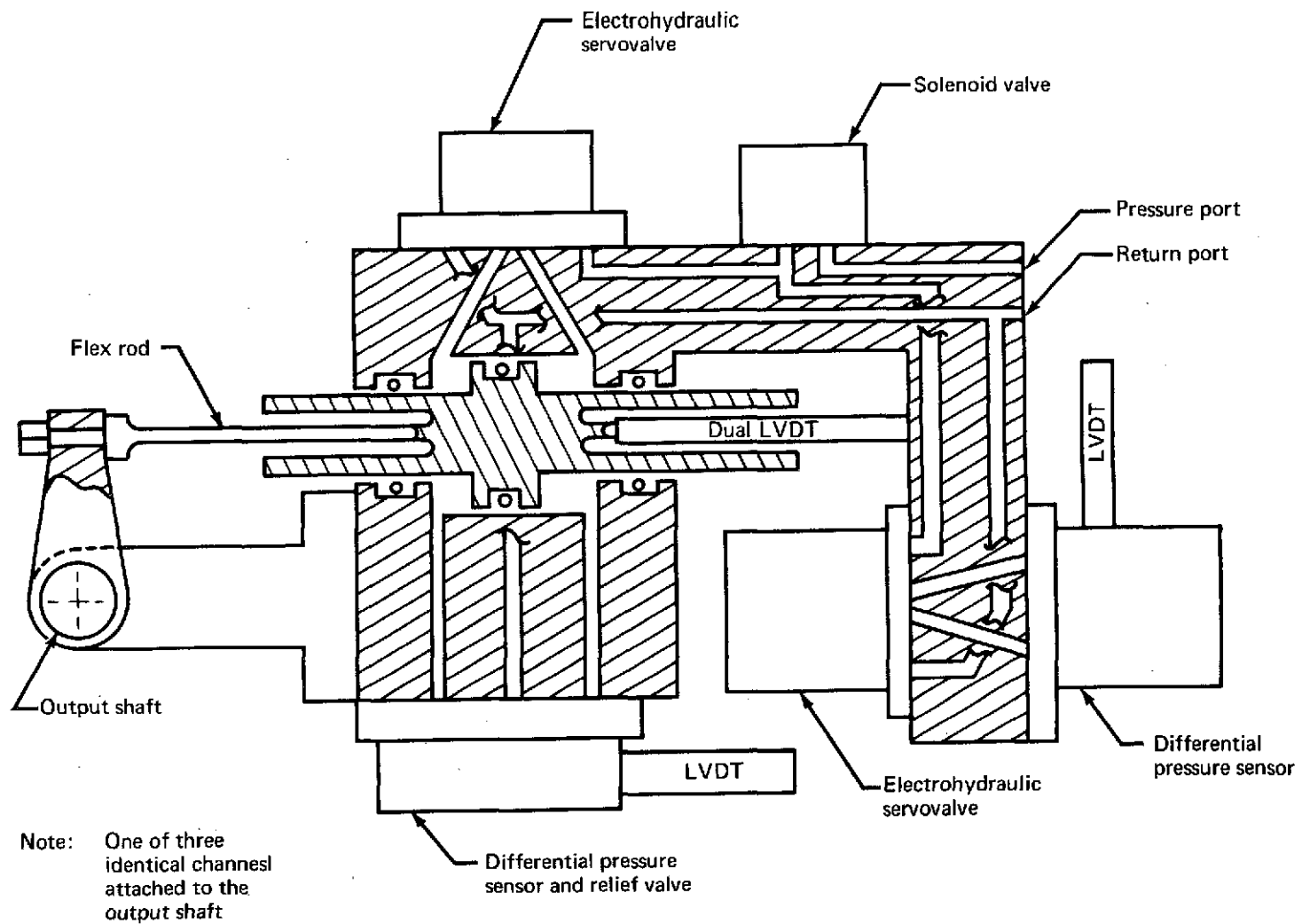


FIGURE 19.—ACTIVE STANDBY ACTUATOR, SINGLE ACTUATOR ELEMENT

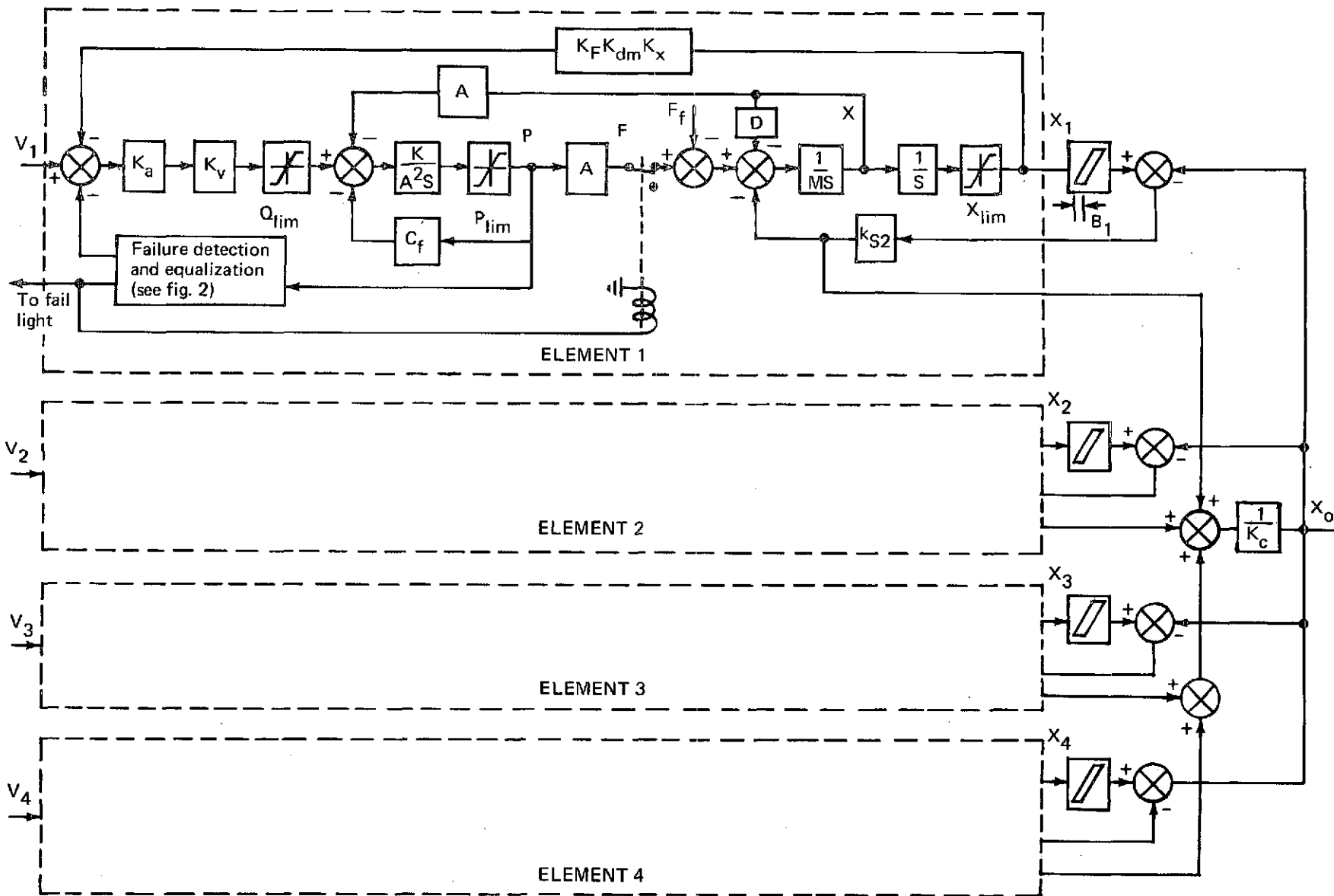
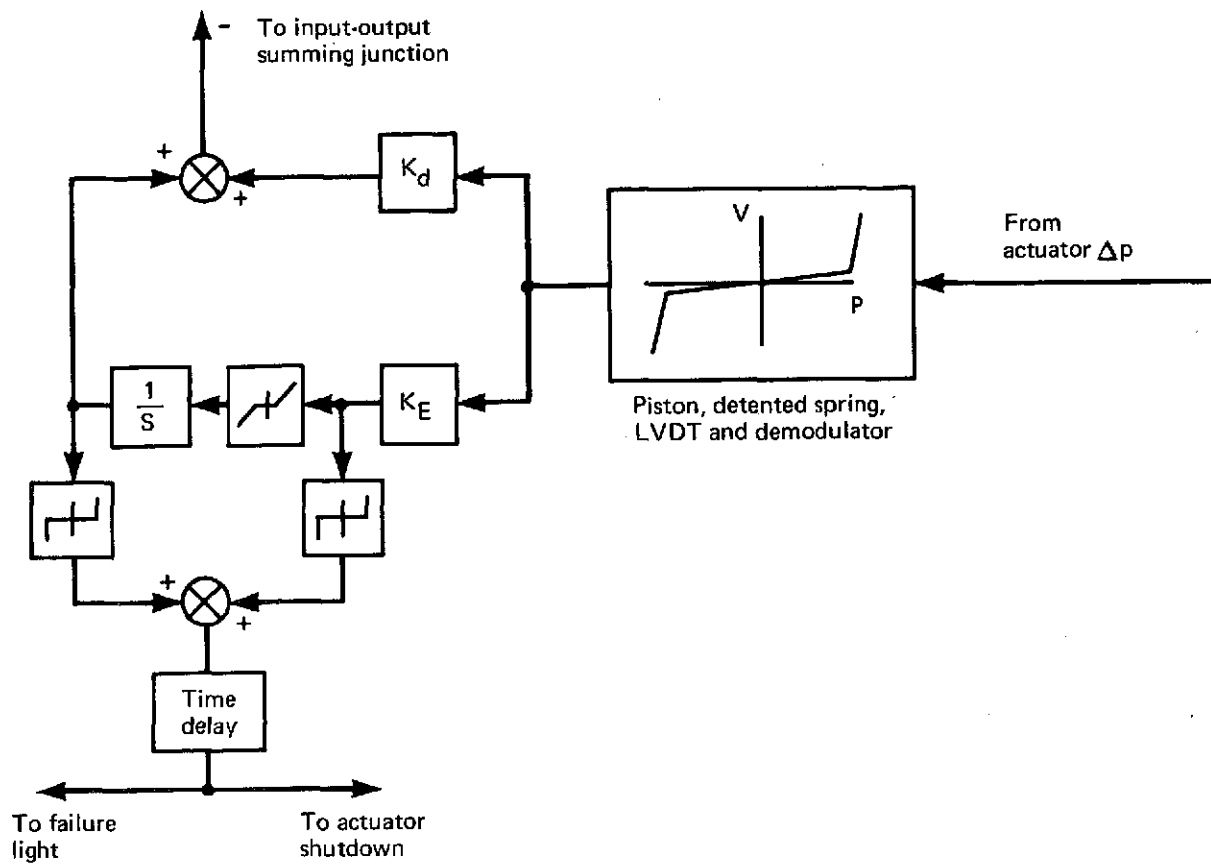


FIGURE 20.—FORCE VOTED MATH MODEL



Note: All values in this diagram will be determined by experimentation in conjunction with the complete actuator model and airplane simulation.

FIGURE 21.—FAILURE DETECTION/EQUALIZATION

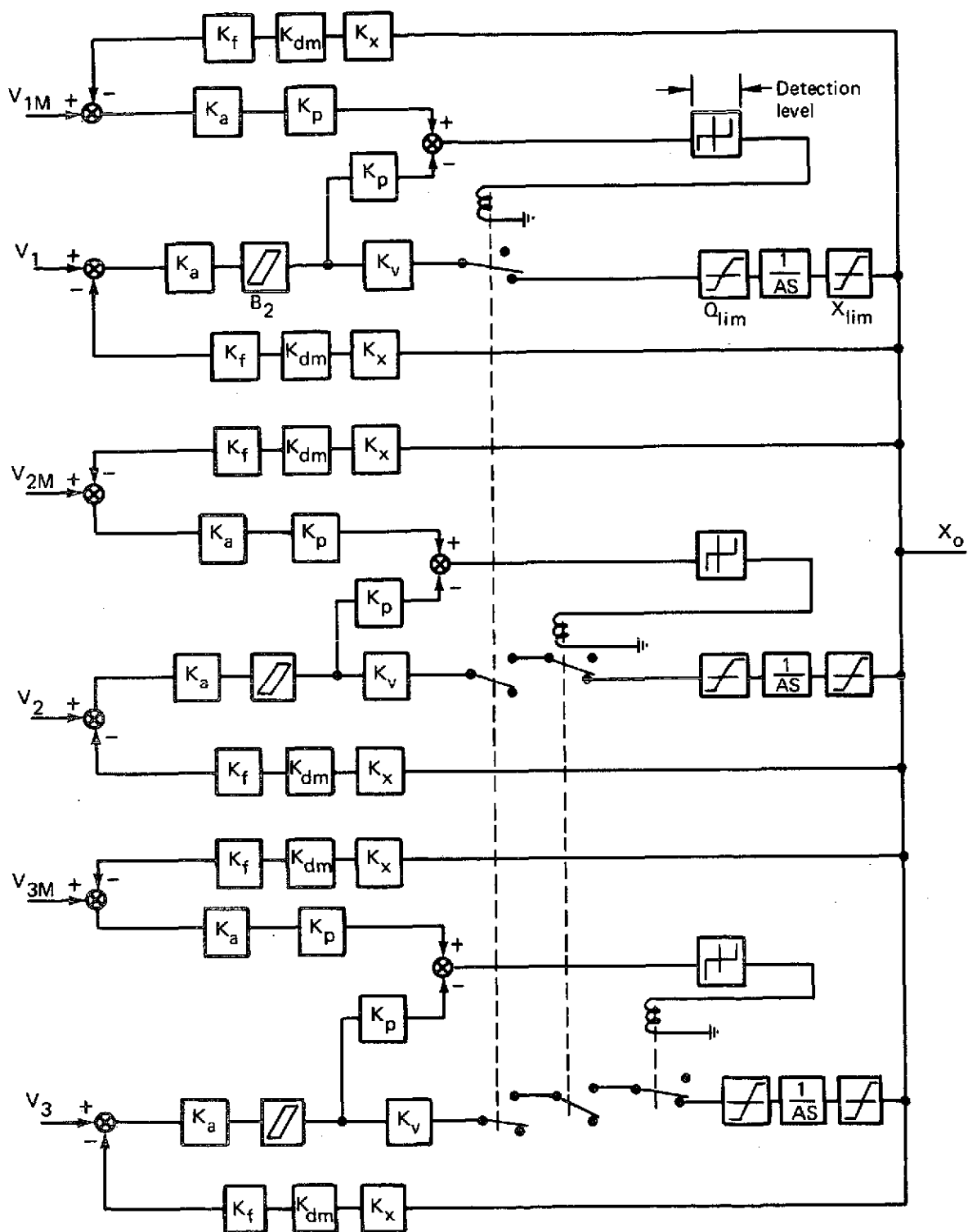


FIGURE 22.—ACTIVE/STANDBY MATH MODEL



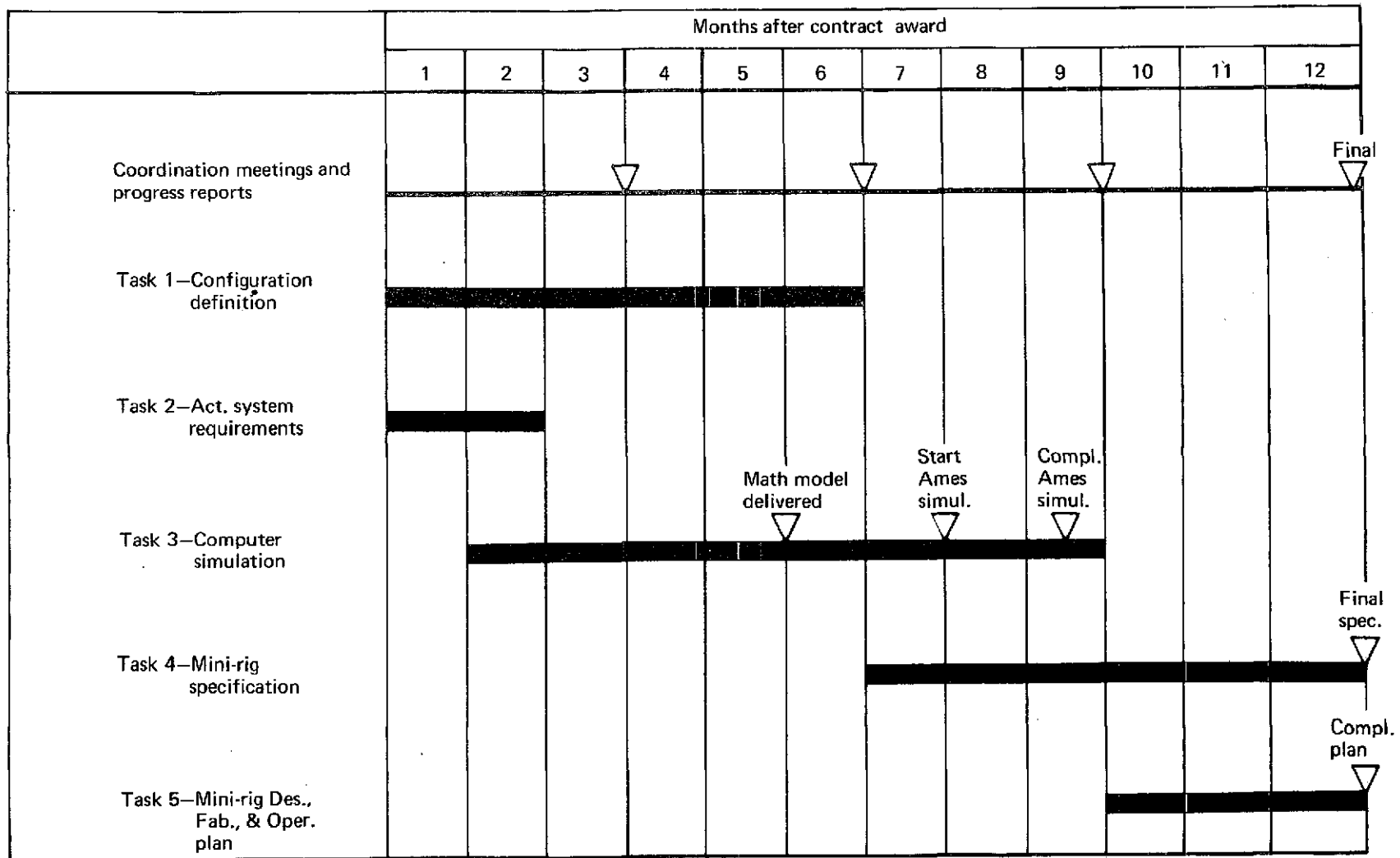


FIGURE 24.—PROGRAM SCHEDULE-PHASE II

TABLE 1
ACTUATOR PARAMETERS

Symbol		Value	
		SI Units	US Units
A	Piston area	$1.9 \times 10^{-4} \text{ m}^2$	0.294 in^2
B ₁	Linkage freeplay	$5.08 \times 10^{-5} \text{ m}$	0.002 in
B ₂	Hysteresis due to friction	$.047 \text{ ma}$	$.047 \text{ ma}$
C _p	Flow gain/pressure gain	$8.78 \times 10^{-13} \frac{\text{m}^3/\text{sec}}{\text{N/m}^2}$	$3.69 \times 10^{-4} \frac{\text{in}^3/\text{sec}}{\text{lb/in}^2}$
D	Damping/channel	$1402 \frac{\text{N}}{\text{m/sec}}$	$8 \frac{\text{lb}_f}{\text{in/sec}}$
F _f	Coulomb friction/channel	17.8 N	4 lb_f
F ₁ , F ₂ etc	Actuator force output	N	lb_f
H ₁	Feedback gain ($K_x K_{dn} K_f$)	204.33 V/m	5.19 V/in
K _a	Servo amp gain	57.6 ma/V	57.6 ma/V
K _c	Centering spring	variable N/m	variable lb/in
K _{dm}	Demodulator gain	1.25 vdc/vac	1.25 vdc/vac
K _f	feedback amp gain	0.296 V/V	0.296 V/V
K _L	Open loop gain	122 sec^{-1}	122 sec^{-1}
K _p	Pressure gain	$2.24 \times 10^6 \frac{\text{N/m}^2}{\text{ma}}$	$325 \frac{\text{lb/in}^2}{\text{ma}}$
K _{S1}	Actuator structural spring	$1.98 \times 10^6 \text{ N/m}$	$1.13 \times 10^4 \text{ lb}_f/\text{in}$
K _{S2}	Actuator rod spring	$3.5 \times 10^6 \text{ N/m}$	$2 \times 10^4 \text{ lb}_f/\text{in}$
K	Actuator dynamic spring $\frac{4A\beta K_{S1}}{K_{S1}L + 4A\beta}$	$2.55 \times 10^7 \text{ N/m}$	$1.46 \times 10^5 \text{ lb}_f/\text{in}$
K _v	Valve flow gain	$1.97 \times 10^{-6} \frac{\text{m}^3/\text{sec}}{\text{ma}}$	$.12 \frac{\text{in}^3/\text{sec}}{\text{ma}}$
K _x	LVDT output	550 v/m	14 v/in
L	Actuator stroke ($2 X_{LIM}$)	$\pm 0.0127 \text{ m}$	$\pm 0.5 \text{ in}$
M	Load mass/channel	20 kg_m	$.114 \frac{\text{lb}_m \text{sec}^2}{\text{in}}$
P _m	Maximum actuator ΔP	6.9 N/m^2	1000 psi
P _T	Bypass pressure	6.4 N/m^2	930 psi
X ₀ , X ₁ etc	Output displacements	m	in
β	Oil bulk modulus	1.03 N/m^2	$150,000 \text{ lb/in}^2$
V ₁ , V ₂ etc	Input signal voltage	V	V

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